MASTER

Stability of axially loaded GFRP sandwich wall panels

Rake, F.G.

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STABILITY OF AXIALLY LOADED GFRP SANDWICH WALL PANELS

MASTER THESIS

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STABILITY OF AXIALLY LOADED GFRP SANDWICH WALL PANELS

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In this Master thesis I present my graduation project about out-of-plane buckling behaviour of axially loaded GFRP sandwich wall panels. The Master thesis has been written to finalize my graduation project at the department of Built Environment. The graduation project is the final project of the Master Architecture, Building and Planning with the specialization Structural Design at Eindhoven University of Technology. The graduation project is carried out in corporation with Ingenieursbureau Wassenaar and Baer BV Sandwich panels.

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Frank Rake
Eindhoven, February 2016
SUMMARY
The demand for modular system in the Built Environment has increased the last decade. Sandwich wall panels substitute the traditional insulated cavity wall by a single element and are able to speed up the buckling process for renovation, houses or apartments. Sandwich panels are able to substitute insulating and structural capabilities into a single element. These sandwich panels do not exist yet as the general knowledge about composites for many engineers is limited. From the structural aspect sandwich wall panels are sensitive to buckling. Analytical or numerical research to these panels has been done quite often. But a combination of analytical or numerical research with experimental tests are exceptional. Experimental tests verified by finite element (FE) analyses are required to describe the buckling behaviour of load bearing sandwich wall panels which results in the research objective:

How can out-of-plane buckling behaviour of fibre reinforced composite sandwich wall panels loaded by uniform uniaxial centric compression be modelled?

Sandwich panels with thin face sheets are sensitive to Euler (global) buckling, wrinkling (local buckling) or coupled instabilities (interaction buckling). These buckling behaviours are described according to the linear sandwich theory [1]–[3]. This theory uses superposition of the core deformation and face sheet bending deformation by the (Euler-) Bernoulli beam theory. According to this theory global buckling will be determined by the reciprocal value of the Euler buckling load and shear buckling load. Since 1867, wrinkling is examined in several papers [4]–[10]. They all conclude that Allen’s formula’s [8] for thin faces agrees well to predict the wrinkling load. Combinations of Euler buckling and wrinkling refer to coupled instabilities. As a result of the Euler buckling mode localization of compression stresses occur in a single face sheet which cause face sheet wrinkling case I – rigid base. Coupled instabilities result in a significant stiffness loss and an axial shortening of the whole panel [11]–[15].

Experimental tests are performed to determine material properties of the glass fibre reinforced polymer (GFRP) face sheet and extruded poly styrene (XPS) core. A statistical analysis proves the relative constant quality of well-engineered materials with small variations. To examine the load conditions small cubic sandwich panels are used. Premature crushing failure of the face sheets due to the applied load is prevented by enclosing the sandwich panel ends over a height of at least 25 mm. Load conditions are used to investigate the lateral buckling behaviour of a GFRP sandwich wall panel. Three face sheet thicknesses are examined (0,8 mm, 1,5 mm and 3,0 mm). Geometrical imperfections in face sheets of 0,8 mm cause wrinkling and result in sandwich panel failure. Thicker face sheets of 1,5 mm and 3,0 mm are less sensitive to wrinkling at the lower load levels. But due to the contribution of a second order effect compression stress localizations result in wrinkling case I – rigid base. Coupled instabilities result in a significant global stiffness loss in sandwich panels with 1,5 mm and 3,0 mm face sheets.

As a result of the assumed hinge conditions in the experimental tests the geometric nonlinear analysis including imperfections (GNIA) of the 2D finite element model underestimates the buckling behaviour. Due to friction the hinge connection behaved as a nonlinear rotational spring stiffness. With respect to the performed experimental tests on the sandwich panels the FE model is unable to estimate the exact buckling behaviour. Hinge connections in experimental buckling tests need to be avoided. Regardless of this observation the range wherefore buckling occurred is given with respect to the first and second buckling modes by a linear buckling analysis. Results of the GNIA give an appropriate prediction of the buckling behaviour. Reasonable geometrical imperfections are applied in the GNIA with respect to Euler buckling and wrinkling or by a range of L/10000 and L/750 and 1-30% of the face sheet thickness respectively.

Keywords: Sandwich panel, XPS, GFRP, Euler buckling, wrinkling, coupled instabilities, experimental tests, GNL analysis, and geometrical imperfections.
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## NOMENCLATURE

### Greek and Latin symbols

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ</td>
<td>Shear angle</td>
<td>Deg or Rad</td>
</tr>
<tr>
<td>δ</td>
<td>Deformation</td>
<td>mm</td>
</tr>
<tr>
<td>ε</td>
<td>Strain</td>
<td>%</td>
</tr>
<tr>
<td>κ</td>
<td>Curvature</td>
<td>mm⁻¹</td>
</tr>
<tr>
<td>λ</td>
<td>Eigenvalue</td>
<td>N</td>
</tr>
<tr>
<td>μ</td>
<td>Friction coefficient</td>
<td></td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td>g/m³</td>
</tr>
<tr>
<td>σ</td>
<td>Stress</td>
<td>MPa</td>
</tr>
<tr>
<td>σ(_{cr,w})</td>
<td>Critical wrinkling stress face sheet</td>
<td>MPa</td>
</tr>
<tr>
<td>σ(_i)</td>
<td>Interfacial tensile stress</td>
<td>MPa</td>
</tr>
<tr>
<td>τ</td>
<td>Shear strength</td>
<td>MPa</td>
</tr>
<tr>
<td>ν</td>
<td>Poison ratio</td>
<td>-</td>
</tr>
<tr>
<td>ν(_c)</td>
<td>Poison ratio core</td>
<td></td>
</tr>
<tr>
<td>ψ</td>
<td>Rotation</td>
<td>Deg or Rad</td>
</tr>
</tbody>
</table>

### Roman symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cross-sectional area</td>
<td>mm²</td>
</tr>
<tr>
<td>A(_m)</td>
<td>Effective core shear area</td>
<td>mm²</td>
</tr>
<tr>
<td>b</td>
<td>Width</td>
<td>mm</td>
</tr>
<tr>
<td>c</td>
<td>Core thickness</td>
<td>mm</td>
</tr>
<tr>
<td>B(_1)</td>
<td>Constant</td>
<td></td>
</tr>
<tr>
<td>D = d</td>
<td>Depth</td>
<td>mm</td>
</tr>
<tr>
<td>D(_E)</td>
<td>Sandwich panel stiffness</td>
<td>Nmm²</td>
</tr>
<tr>
<td>D(_f)</td>
<td>Bending stiffness face sheet only</td>
<td>Nmm²</td>
</tr>
<tr>
<td>E</td>
<td>Modulus of elasticity</td>
<td>MPa</td>
</tr>
<tr>
<td>F</td>
<td>Force</td>
<td>N</td>
</tr>
<tr>
<td>G</td>
<td>Shear modulus of elasticity</td>
<td>MPa</td>
</tr>
<tr>
<td>h</td>
<td>Height</td>
<td>mm</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
<td>mm</td>
</tr>
<tr>
<td>L(_{CR})</td>
<td>Buckling length</td>
<td>mm</td>
</tr>
<tr>
<td>L(_W)</td>
<td>Half sine wrinkling wave length</td>
<td>mm</td>
</tr>
<tr>
<td>n(_1)</td>
<td>Imperfection buckling mode 1</td>
<td>mm</td>
</tr>
<tr>
<td>n(_2)</td>
<td>Imperfection buckling mode 2</td>
<td>mm</td>
</tr>
<tr>
<td>P(_{CR})</td>
<td>Global buckling load</td>
<td>N</td>
</tr>
<tr>
<td>P(_E)</td>
<td>Euler buckling load</td>
<td>N</td>
</tr>
<tr>
<td>P(_s)</td>
<td>Core shear buckling load</td>
<td>N</td>
</tr>
<tr>
<td>S(_d = s)</td>
<td>Standard deviation</td>
<td>-</td>
</tr>
<tr>
<td>t</td>
<td>Face sheet thickness</td>
<td>mm</td>
</tr>
<tr>
<td>U</td>
<td>Translational DOF</td>
<td>mm</td>
</tr>
<tr>
<td>UR</td>
<td>Rotational DOF</td>
<td>Rad</td>
</tr>
</tbody>
</table>

The index 1,2,3 or x,y,z refers to the used coordinate system.
1. INTRODUCTION

Nowadays, sandwich panels of fibre reinforced composites (FRC) are mostly applied in industry, boats, aircrafts, and façades. Hybrid materials like FRC are used when separate materials cannot meet the specification requirements. The main advantage of FRC is their capability to combine the positive characteristics of two or more materials. Composite materials have a low weight and a high strength. A composite is a composition of two or more materials differing in form or in composition on a macro scale. In fibre reinforced composites, fibres are used as reinforcement combined with a weaker material like polymers as matrix. The matrix fulfils the glue connection between fibres and increases the compressive strength of fibres. Fibres only carry tension forces, while the combination of fibres and matrix can withstand compression forces. The weaker material is always the polymer matrix, however it is required to glue all fibres together to a composite element. Composites are used to sandwich panel face sheets. The core material of a sandwich panel is constructed of a lightweight extruded polystyrene (XPS) foam. The combination of a high strength and high stiffness face sheet with a lightweight foam core results in a sandwich panel with an excellent low weight to strength ratio.

Façade panels and load bearing roof or floor structures are some examples of composite sandwich panels applied in the Built Environment. Similarities within these structures are the thermal insulation of the foam core and the structural behaviour. The latter, the structural behaviour divides these examples into primary and secondary structures. The roof and floor structures are primary structures that provide the load bearing ability of a building. Façade panels are only used to secondary structures. Fibre reinforced polymers (FRP) have been applied in façade panels in the Built Environment since a few years. These panels have many advantages regarding to architectural design aspects. The most important advantage of FRP panels for architects is the high freeform capability of FRP panels. These panels fulfil the secondary structural function in a building. They are only self-load bearing panels and transfer wind loads to the primary structure that is behind the FRP panel. The City Hall (Figure 1) in Utrecht nearby central station is an example for façade panels made from glass fibre reinforced polymer (GFRP). The R-value (measure for thermal resistance) for such a façade panel lies between 8,0 and 11,5 m²K/W with a corresponding thickness of approximately 300 mm.

![Figure 1: Left: City hall Utrecht; Nedcam. Right: Façade panel; CU2030.](image)

The thermal insulation, the high freeform capability and the load bearing behaviour are three important features that can be fulfilled by a single sandwich wall panel. The demand for modular systems in the Built Environment has increased in the last decade. A sandwich wall panel substitutes the traditional insulated cavity wall by a single element to speed up the building process for renovation, houses, offices, pavilions, apartments, rooftop buildings or buildings on floating islands. These sandwich wall panels do not exist yet as the general knowledge about composites for many engineers is limited or the starting costs for a die or mould in the manufacturing process are too high. Load
bearing façade panels can increase the building process and save costs. From the structural aspect sandwich wall panels are sensitive to buckling. Analytical or numerical research to sandwich panel buckling and to optimise the influence of foams to the face sheet material has been done quite often. But a combination of analytical or numerical research with experimental tests are exceptional. According to [16]–[19], experimental tests verified by a numerical or an analytical analysis are required to describe buckling failure behaviour of load bearing sandwich wall panels.

### 1.1 RESEARCH OBJECTIVES

Structural fibre reinforced composite sandwich wall panels will be further named as ‘FRC sandwich wall panels’. For this research it is assumed that FRC sandwich wall panels are non-stabilising elements. Staircase walls, elevator shafts, or wind braces are used to stabilise structures. Horizontal forces caused by wind pressure to the façade are supported by structural floors. These floors are capable to take horizontal forces into account and transfer those forces to stabilising elements. Vertical forces of floors or upper walls are introduced as uniformly distributed load at top of the FRC sandwich wall panel. Additional loads through thermal behaviour, fire, collision, etcetera will not be taken into consideration. Given the fact that compression elements will be used as load bearing walls, this leads to the first objective of this research:

*How can out-of-plane buckling behaviour of fibre reinforced composite sandwich wall panels loaded by uniform uniaxial centric compression be modelled?*

![FRC Sandwich panel](image)

Figure 2: FRC Sandwich panel.

The sandwich panel is only subject to uniform uniaxial centric compression loads from upper structural elements such as roofs, walls and floors. As mentioned before, a FRC sandwich wall panel exists of a foam core surrounded by two outer FRC face sheets (Figure 2). The bond between the foam and face sheets is made from an adhesive material which is capable to take shear- and tension forces into account.

A brief explanation is necessary to explain the aim of this research by a few sub questions. Firstly the mechanical properties of the constituent sandwich panel materials are required. These mechanical properties can be used in the following sub question:

1. *How can the exact buckling load be determined?*
The experimental research contains some tests to determine the mechanical properties of the sandwich panel face sheet material and the core material. Furthermore, to investigate the buckling behaviour of a sandwich panel requires a full-scale buckling test. The result of the experimental tests can be used to solve the second subquestion:

2. Can a model be built which is able to predict buckling of FRC sandwich panels?

The experimental research shows insight to the sandwich panel buckling behaviour and their critical modes. The result of the experimental tests will be used to develop a numerical model. The mechanical properties measured in the experimental research and the buckling behaviour of the full-scale sandwich panel buckling test are the input parameters of the numerical model. The numerical model must be able to predict the buckling behaviour and buckling load. It is important to emphasize that buckling in this context means any type of sandwich buckling, namely:

− Global buckling;
− Shear buckling; or
− Wrinkling face sheets (i.e. local buckling); or
− Coupled instabilities.

These buckling types will be explained in more detail in the literature study. Wrinkling occurs over a local area and is a stability problem in thin walled plates like FRC face sheets supported by a medium as foam. Wrinkling of thin walled plates leads to forces in the longitudinal and transverse direction when a uniform compression load is applied in one of those directions. This research focuses on the dominant buckling type which occurs at experimental tests to the sandwich wall panels. It will give more knowledge to fibre reinforced composite sandwich wall panels used as a vertical load bearing wall element.
2. LITERATURE STUDY

This chapter distinguishes four main sections of which the first section describes the constituent materials of a sandwich panel and their material behaviour. The second section explains different sandwich panel theories and sandwich panel buckling behaviour. The sandwich panel buckling behaviour face sheet wrinkling (i.e. local buckling) is highlighted in the third section by a summary of relevant articles about face sheet wrinkling. Finally, the fourth section treats the individual sandwich panel failure mechanisms.

2.1 COMPOSITE FACE SHEET

Composite materials are a mixture or combination of two or more macroscopic components which result in a useful third material. This new material has only characteristics that are necessary to perform the design task. Some properties of composites that can be improved by changing material combinations [20] are:

- strength;
- stiffness;
- corrosion resistance;
- wear resistance;
- attractiveness;
- weight;
- fatigue life;
- temperature dependent behaviour;
- thermal insulation;
- thermal conductivity;
- acoustical insulation.

High strength to weight and stiffness to weight ratios are important in lightweight composites of fibre/resin materials. Composite materials can be produced with the same strength and stiffness as high strength steel, but 70 percent lighter.

2.1.1 Fibre and matrix materials

Fibre reinforced composites are excellent to use for applications of lightweight structures. To understand their material behaviour a brief explanation will be given according to the constituent materials of fibre reinforced composites. These materials are a homogeneous matrix (resin) component which is reinforced by a stiffer and stronger component. The stiffer and stronger components are usually fibres, or particulates (tiny solid parts), or other shapes. Fibres are used as reinforcement to take tensile forces into account, and the matrix (resin) mostly compression forces. Table 1 gives fibre mechanical properties like density, strength, stiffness, strain, and a linear coefficient of thermal expansion of common fibres in comparison to S235 steel.
Table 1: Comparison fibres [21], [22].

* = 1 GPa = 1000 MPa is 1000 N/mm².
** = Linear Coefficient of Thermal Expansion at 20 degrees Celsius.

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>E-glass</th>
<th>Bamboo</th>
<th>Kevlar 49</th>
<th>Carbon high modulus</th>
<th>Steel S235</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ($\rho_f$)</td>
<td>[g/m³]</td>
<td>2,54</td>
<td>0,4-0,8</td>
<td>1,45</td>
<td>2,15</td>
<td>7,85</td>
</tr>
<tr>
<td>Tensile stress ($\sigma_u$)</td>
<td>[MPa*]</td>
<td>3450</td>
<td>100-200</td>
<td>3620</td>
<td>2410</td>
<td>310-510</td>
</tr>
<tr>
<td>Tensile modulus ($E_t$)</td>
<td>[GPa]</td>
<td>72,4</td>
<td>10-15</td>
<td>131</td>
<td>758</td>
<td>210</td>
</tr>
<tr>
<td>Strain ($\varepsilon$)</td>
<td>[%]</td>
<td>4,8</td>
<td>-</td>
<td>2,8</td>
<td>0,32</td>
<td>0,2</td>
</tr>
<tr>
<td>LCTE ($\alpha$)**</td>
<td>[$10^{-6}$/K]</td>
<td>5</td>
<td>-</td>
<td>-2</td>
<td>-1,45</td>
<td>12</td>
</tr>
</tbody>
</table>

Differences in tensile strength and tensile modules of fibres to steel are remarkable. Table 1 can also be displayed graphically, as displayed in the Ashby plots in Figure 3.

![Ashby plots](image)

Figure 3: Ashby plots of mechanical properties of composite material; [23].

In the left Ashby plot in Figure 3, polymers and composite materials are shown. Composites have approximately a similar Young’s modulus compared to metals and alloys. However, composites are lighter. The right Ashby plot in Figure 3 plots, for polymers, glasses, and composites, their specific stiffness ratios at the vertical axis to specific strength ratios at the horizontal axis. The strength and stiffness are normalised by a material density. Glass fibre reinforced polymer (GFRP) and carbon fibre reinforced polymer (CFRP) have the same specific stiffness as metal and alloys. Moreover the strength of composites are equal or even better then strength of metals and alloys.

Fibres are useless without surrounding matrix (resin) to perform in a structural member. The matrix is a homogeneous binder material that supports fibres, protects fibres, and transfers stresses between fibres. Stresses are transferred from matrix to fibres by a chemical or mechanical bond. Matrix materials can be:

- polymers;
- metals;
- ceramics;
The matrix materials are listed in ascending order of their temperature resistance and costs. Polymers and carbon are mostly used in structural applications. Polymers can be further divided into rubbers, thermoplastics and thermosets. Thermoplastics (e.g., nylon, polyethylene, and polyamide) can repeatedly softened by heating and hardened by cooling. In contradiction to these thermoplastics, thermosets are not able to change their form after heating. Thermosets (e.g., epoxy, polyester and vinyl ester), are polymers that are chemically bonded into an irreversible three-dimensional network. That implies that once a polymer is set, it cannot be changed into another form.

2.1.2 Composite material behaviour

Classic engineering materials (e.g., steel, timber, concrete, and aluminium) have less mechanical behaviour properties as composites materials. Common engineering materials are mostly homogeneous and isotropic in contradiction to composite materials. Composite materials are mostly heterogeneous and non-isotropic (e.g., orthotropic or anisotropic). Isotropic, orthotropic, and anisotropic material behaviour under loading of normal stress and shear stress are shown in Figure 4:

- An isotropic body subjected to a normal stress extends in the stress direction, contracts in the perpendicular direction, and causes no shearing deformation. The same isotropic body subjected to a shear stress causes only shearing deformation without any extension or contraction. Material properties of Young’s modulus, shear modulus, and Poisson’s ratio are coupled and lead to two unknown material properties.

- An orthotropic body subjected to a normal stress behaves similar to an isotropic body, but the magnitude of extension in one principal material direction can be different from another principal material direction under the same conditions. So, it consists of different Young’s modulus, and different Poisson’s ratios in two principal directions. Shear deformation due to shear stress occurs independent of Young’s moduli and Poisson’s ratio. Thus, the shear modulus does not depend on other material properties, and leads to at least five unknown material properties.

- An anisotropic body subjected to a normal stress extends in the stress direction, contracts in the perpendicular direction, but deforms also under shear. An anisotropic body loaded by a shear stress causes
these three similar deformation modes. This shear-extension coupling also occurs in an orthotropic body loaded in a non-principal material direction. An anisotropic body has even more material properties than orthotropic materials.

A fibre loaded by a tensile stress is stiffer, stronger, and less ductile than a matrix (resin) component in a composite. In general, the stress/strain diagram of fibres are linear elastic and the stress/strain diagram of the matrix is non-linear elastic. This result into a non-linear elastic stress/strain behaviour of composite as can be seen in Figure 5. Strength and stiffness strongly depends on the laminate structure of composite (see subsection 2.1.3).

![Tensile stress/strain diagram for typical fibre, matrix, and composite.](image)

**Figure 5: Tensile stress/strain diagram for typical fibre, matrix, and composite.**

### 2.1.3 Laminate

Fibres have high strength and stiffness, and resin is the glue between fibres. Glue is better known as matrix and surrounds fibres to increase the compression strength of fibres as mentioned before. Material properties are related to a laminate of fibre reinforced polymers. A laminate is a stack of symmetrical or unsymmetrical laminas (plies) which can point into four directions (e.g., 0°, ±45° and 90°).

The basic building blocks (see also Figure 6) to construct fibre reinforced composites are:

- matrix;
- fibre types;
- laminate: symmetrical or unsymmetrical stack of lamina layers;
- fibre ratio to matrix;
- manufacturing technique;
- coupling agent or fibre surface coating;
- fillers and other additives.
A coupling agent or fibre surface coating improves the load transfer between fibre and matrix. It also improves the wetting process during the manufacturing of composites. The fillers and other additives reduce costs, and mould shrinkage, increase the modulus of elasticity, produce smoother surface, and control viscosity.

Combining these aspects leads to the most common used structural composite, namely glass fibre reinforced polymer (GFRP). Changing a single aspect can alter all mechanical properties of this composite. A first assumption of characteristic properties of a laminate can be predicted by the so-called ‘classical laminate theory’ [24]. Experimental tests are necessary to verify assumptions for the design phase. The laminate theory is based on the Euler-Bernoulli beam theory and Kirchhoff-Love theory of thin plates [22]. It simplifies complicated three-dimensional elasticity to a solvable two-dimensional mechanics of deformable body problem. Unidirectional composites represent the basic element in the modelling of all laminates or 2D or 3D fabrics. They are considered as orthotropic materials composed of reinforcement (fibres) and matrix (resin). The classical laminate theory (CLT) can be used to describe mechanical properties of laminated solids and shells. Each lamina (plies) equal in thickness may have a different orientation (e.g., 0°, ±45° and 90°) or unique material composition. A thin plate or a shell can be described by three in-plane forces and three moments. Relations between external loadings (i.e., forces N and moments M), and displacements (strains ε and curvatures κ) of a composite material can be written into an ABD matrix (Figure 7).
Figure 7: Stiffness terms ABD matrix expressed in forces and moments; [20].

The extensional stiffness and bending stiffness in the ABD matrix are described by:

- $A$ are extensional stiffness's;
- $B$ are bending-extension coupling stiffness's;
- $D$ are bending stiffness's.

Forces and moments might simultaneously occur in a thin plate. The stiffness parameter $B$ describes a coupling between extensions and bending stiffness's. Therefore, it is impossible to construct a matrix with only $B$ terms. All $B$ components can only be zero when the laminate structure is exactly symmetric about the middle surface of the laminate. It also requires symmetry in lamina properties, distance from the middle surface and orientation. Shear-extension coupling (parameters $A_{16}$ and $A_{26}$) does not occur in orthotropic materials loaded in principal directions, but it occurs in other loading directions.

### 2.1.4 Mechanical properties

Firstly, various micro-mechanical models [25] can predict mechanical elastic properties of unidirectional (UD) composites. Two well-known models are Voigt and Reuss. These models are based on the following assumptions:

- fibres are uniformly distributed in the matrix;
- fibres and matrix are bonded well;
- matrix is free of voids;
- applied loads are normal or parallel to fibre direction;
- lamina is free of residual stresses in a free stress state;
- matrix and fibres are linear elastic materials.

The Voigt model can be presented as Rule of Mixture or iso-strain model:

$$E_{11} = V^f E_{11}^f + V^m E^m$$

(1)
\[ \nu_{12} = V_f \nu_{11} + V_m \nu_m \]

The Reuss model as inverse rule of mixture or iso-stress model:

\[ E_{22} = \frac{E_{22}^f E_m}{E_m V_f + E_{22}^f V_m} \]
\[ G_{12} = \frac{G_{12}^f G_m}{G_m V_f + G_{12}^f V_m} \] (II)

These models use five independent engineering constants: longitudinal and transversal moduli of elasticity \( E_{11} \) and \( E_{22} \), longitudinal and transversal shear moduli of elasticity \( G_{12} \) and \( G_{23} \), and the Poisson ratio \( \nu_{12} \). Effective elastic properties are expressed in terms of the mechanical properties of fibres and matrix material. The fibre volume fraction and matrix volume fraction are respectively \( V_f \) and \( V_m \).

Three other approach models to describe these similar material properties are:

- semi-empirical models: Modified Rule of Mixture, Chamis model, and Halpin-Tsai model;
- Elasticity approach: Hashin and Rosen, and Christensen;
- Homogenization models: Hill, and Budianski.

Secondly, in contrast to these models the compression properties of composites are also important. The compressive strength of GFRP composite is lower than its tensile strength. Fibres of composite usually carry loads in tension and compression. Contradictory to the tensile strength, the compressive strength is more difficult to determine. The matrix (resin) supports fibres especially in compression to prevent failure (i.e., matrix yielding, fibre crushing, and fibre micro-buckling) on material level. A various number of theories (e.g., Rosen and Hanasaki and Hasegawa, Wang, Argon, Fleck and Budiansky) [26] have been developed to predict the compression strength. These theories depend on several properties of resin and fibre:

- Fibre ratio;
- fibre type;
- type of resin (matrix);
- fibre orientation.

In unidirectional (UD) pultruded FRC (fibre reinforced composites) compressive strength can be assumed as 55 percent of their tensile strength [27]. Another research showed a difference of 20 percent between compression- and tensile strength in unidirectional (UD) GFRP laminate [28]. The modulus of elasticity was also investigated and led to similar results at compression and tension.

Furthermore, research of several investigators about the recent developments in the modelling and behaviour of advanced sandwich constructions are summarised [29]. Geometrical linear and non-linear formulations of flat and curved sandwich panels are included. These panels are subjected to stability problems. Face sheets are made of laminated orthotropic face sheets. Results showed that the buckling strength and post-buckling strength increased noticeable by the use of plies in more than one direction (0, 90, +45, and -45 degrees). It also presents an increased buckling strength, and decreased behaviour of snap-through-buckling by the improvement of load carrying capacity of sandwich structures.
Then, codes to use composites in the Dutch Built Environment are unavailable. However, some guidelines of the CUR recommendation 96 [30] for fibre reinforced plastics in Civil Engineering (Dutch code) can be used to derive the mechanical properties from the test data. Characteristic material properties are determined for at least 10 specimen tests (n) per characteristic value. The characteristic strength \( R_k \) (in N/mm\(^2\)) is extracted from the average strength value \( R_m \) (in N/mm\(^2\)) of 10 specimen tests minus two times the standard deviation \( s \) (in N/mm\(^2\)):

\[
R_k = R_m - 2.0 \cdot s \quad \text{(III)}
\]

The characteristic stiffness value \( E_k \) is equal to the average stiffness value \( E_m \) of at least 10 specimen tests:

\[
E_k = E_m \quad \text{(IV)}
\]

### 2.2 FOAM CORE

A sandwich panel subjected to a normal force collapses by local or global buckling in general. The two outer face sheets account for the flexural stiffness and load bearing forces in sandwich panels. Face sheets are subjected to tensile and compressive stresses caused by bending only if the core material is stiff enough to keep a constant distance between outer face sheets. The core material must be so rigid in shear that the face sheets will not slide over the core material. A weak core material prevents corporation of constituent materials in sandwich panels. In lightweight structures insulation, shear rigidity, and a low density are important properties of core materials. Rigid core materials can be:

- polymeric foam;
- syntactic cores (hollow spheres in a resin matrix);
- wood (balsa) cores;
- honeycomb and corrugated (trapezium geometry) cores.

The first and the latter are most used in sandwich structures nowadays. A honeycomb core is the most costly and less insulating material. Common polymeric foams are expanded polystyrene (EPS foam), extruded polystyrene (XPS foam), and polyvinylchloride (PVC foam).

Surveys on the mechanical properties of foams are provided by Gibson and Ashby et al. [31]. Material properties of the Young’s modulus \( E^* \), shear modulus \( G^* \) and bulk modulus \( K^* \) are expressed for an isotropic foam in terms of the cell-wall modulus, \( E_s \), and the relative density, \( p^* / p_s \), of the foam itself. The relative density leads to the degree to which the cells are open or closed with foam density, \( p \), and cell structure \( p_s \). Data for \( v^* \) (Poisson ratio) for closed-cell foams and open-cell foams have nothing in common with density. The Poisson ratio, for closed and open cells, is the ratio of two strains depending on the details of the cell shape but not on the relative density of foams. The cell shape refers to its cell structures. But regardless of open cell or closed cell foams, the Poisson ratio can be approximated by \( v^* \approx 1/3 \).

### 2.3 ADHESIVE

A sandwich panel is useless without a decent adhesive. Firstly, the adhesive prevents slipping of outer face sheets over the core material. Secondly, the outer face sheets are attached to core material by the same adhesive. Due to wrinkling of outer face sheets tensile stresses in the adhesive interface might occur. So finally, the adhesive between outer face sheets and core material must be capable to transfer shear stresses and tensile stresses.
The Euler-Bernoulli beam theory assumes an infinitely rigid cross section in its own plane. Deformations in a sandwich panel cross section are restricted. So, a full connection between outer face sheets and core material is required. The manufacturing technique also contributes to a full connection in sandwich panels. These aspects can be met by choosing an adhesive with a higher shear and tensile stress than the core material. By use of this adhesive a full connection can be assumed.

2.4 SANDWICH PANEL THEORY

Common engineering materials are made of isotropic materials with solid cross sections. Slender beams subjected to transverse loads cause bending and shear deformations. Shear deformations are relatively small compared to bending deformations, so that shear deformations can be neglected. This is described by the (Euler-) Bernoulli beam theory (Figure 8). It assumes that the cross section is infinitely rigid in its own plane, remains normal to the deformed axis of the beam, and remains plane after deformation.

A second model assumes that shear deformations are necessary to take into account deep beams (i.e., beams with a relative high cross section compared with the beam length). The largest shear deformations take place at the highest shear stresses, namely at the neutral axis of the cross section. The rotation of the cross section is no longer equal to the rotation of the beam axis due to shear deformations. This secondary model is described by the Timoshenko beam theory (Figure 8).

![Figure 8: Left: Bernoulli beam theory. Right: Timoshenko beam theory.](image)

Both discussed theories are insufficient to describe bending behaviour of sandwich panels. Bending deformations of sandwich panels are taken by the face sheet material and shear deformations by the core material. The glue, i.e., a continuous bonding surface between the core material and face sheets is assumed to be rigid. It has no contribution to either shear deformations or bending deformations, so the glue material will be neglected. A model that describes sandwich panels with thin face sheets under bending is the linear sandwich theory (Figure 9).
It assumes:

- the core thickness does not change in thickness direction, i.e., the transverse normal stiffness of the core is the same over the length of the beam;
- the core does not extend or shorten in longitudinal direction, i.e., the in-plane normal stiffness of the core is small compared to face sheets;
- face sheets behave according to Bernoulli assumptions. There are no xz shear stresses in the face sheets and face sheets do not change in thickness direction.

Essential in the linear sandwich theory is that shear strains in the core material of a sandwich beam may not be neglected. The core material has a low shear modulus (G). Due to shear deformations the core cross section rotates and the two outer face sheets remain normal to the deformed axis of the beam. So, linear sandwich theory describes a sandwich beam under bending by superposition of core material shear deformations and face sheet bending deformations by Bernoulli beam theory. Moreover, the linear sandwich theory can be found in the next subsection about global buckling. Other types of buckling are coupled instabilities and wrinkling, i.e., local buckling. These three types of buckling will be discussed in the following subsections.

### 2.4.1 Global buckling

According to the assumptions of the linear sandwich theory three models can be described to determine the global buckling load of sandwich panels:

1. Allen’s formula for thin faces;
2. High-order sandwich panel theory;
3. Extended high-order sandwich panel theory.

These theories distinguish stiffness parameters, especially core stiffness’s, of sandwich panels by their constituent materials. The bending stiffness (EI) is taken into account by the face sheet material in all three theories. First of all, Allen’s theory of thin faces only assumes the core shear stiffness (AG) [32] with \( \tau_{xz} = G \gamma_{xz} \). Core shear strains and core bending stiffness are ignored. Secondly, high-order sandwich panel theory (HSAPT) assumes the core shear stiffness (AG) and a contribution of the transverse stiffness of the core by the modulus of elasticity (E_{tc}) in thickness.
direction [1]. The modulus of elasticity is related to the transverse stress of the core with \( \sigma_{zz} = E_{tc} \varepsilon_{zz} \). The HSAPT can only be used for weak cores. Finally, extended high-order sandwich panel theory (EHSAPT) assumes core shear stiffness (\( AG \)), core transverse stiffness (\( E_{tc} \)) and axial core stiffness (\( EA \)). The material behaviour of the axial core stiffness can be either linear or non-linear [2]. EHSAPT can be used for weak and strong cores.

Allen’s thin face theory, HSAPT and EHSAPT are extremely useful to describe global buckling behaviour of sandwich panels loaded by a normal force. Allen’s formula for thin faces (see section 2.5) agrees well as first assumption of the global buckling load [1]–[3].

### 2.4.2 Local buckling (wrinkling)

This paragraph is an introduction to section 2.5 of the literature study. Models to predict wrinkling behaviour will be discussed in this paragraph. Winkler introduced a mechanical representation of soil foundation in 1867 [4]. Vertical deformations of the foundation are described by an infinite set of uncoupled linear elastic springs. This theory can be used to model tensile stresses between outer face sheets and core material of a sandwich panel. Core material behaves similar to an elastic foundation as has been discretised by a set of linear elastic springs.

Between 1940 and 1960 most research to uniaxial compression loaded sandwich structures has been done by Gough and Allen. The elastic Winkler-type foundation was used to model the core. Biaxial loading to isotropic sandwich panels were first analysed by Plantema in 1966. Biaxial loading conditions are used to composite structures of aircrafts. Sullins [5] suggested a criterion of wrinkling under compression in the principal directions. This criterion is formulated to an equation which consists of ratios between the principal compressive stresses and the corresponding wrinkling stresses. The first orthotropic facings in a sandwich structure were observed by Fagerberg, Vonach, and Rammerstorfer recently. Nui and Talreja considered an Euler beam on a Winkler foundation with debonds subjected to in-plane compression [6]. Results showed that perfect bonded face layers can be used to predict the debond length of relatively long face layers by ratio of the wrinkling wavelength.

Structural insulated sandwich panels are proposed as a new type for structural floor and wall applications [7]. The core material consists of expanded polystyrene (EPS) foam surrounded by face sheets of orthotropic thermoplastic glass/polypropylene laminate. Interfacial tensile stresses and critical wrinkling in-plane stresses are presented by models with debonding of the face sheet or core. The main failure mode is face sheet or core debonding with a half-wavelength approximately equal to the core thickness [7], [8]. In 1954, Pasternak proposed a model that includes shear interaction between springs. Later, Kerr developed a foundation model that is precise. Instead of a fourth order differential equation is a sixth order differential equation used to model an elastic foundation [9]. In the Kerr model a second Winkler foundation on top of the Pasternak foundation is placed (Figure 10).

![Figure 10: Beam on a two parameter elastic foundation; [4].](image-url)
Later on another approach was developed, a differential set of compatibility, constitutive, and equilibrium equations to describe behaviour of the soil or core material as a semi-infinite continuum. Assumptions were made with respect to displacements and stresses to simplify those differential equations to an exact, closed-form model. This is better known as simplified-continuum modelling. Reissner and Vlasov (1960) made modifications to the simplified-continuum model using a model that describes response of loading nearby a contact area.

In 1969, Allen constructed a theory specially for sandwich panels subjected to a normal force to predict face sheet/core debonding, i.e., wrinkling to predict critical wrinkling stresses in the outer face sheet (see Figure 11). Between the outer face sheet and core material interfacial stresses or tensile stresses occur. To derive this analytical problem three models were used:

- case I: rigid base;
- case II: asymmetrical wrinkling;
- case III: symmetrical wrinkling.

These three types of wrinkling are recommended often in research [5]–[7], [33]. Plantema, and Hoff and Mautner are also frequently used models to predict wrinkling of sandwich panels. Hoff’s formula can only be used in orthotropic fibre reinforced face sheets which are isotropic through the thickness of the face sheet of sandwich panels [34].

Several papers have been written about wrinkling instability of sandwich panels, namely by Mousa [7], [33], Birman [5], Niu and Talreja [6], Allen [8], Zenkert [10], and Fagerberg [34]. They all state that Allens perform well. Section 2.5 uses these formulas to predict wrinkling stresses.

### 2.4.3 Coupled instabilities

A perfect linear framework loaded in compression will fail either to local buckling (case II or III) or global buckling (Euler). As a result of the Euler buckling mode localization of compression stresses occur in a single face sheet which cause face sheet wrinkling case I – Rigid base (local buckling). Failure due to coupled instabilities results in a significant stiffness loss and an axial shortening of the whole sandwich panel [11]–[15]. The magnitude of the compression stresses can be similar to both the instability modes face sheet wrinkling and Euler buckling. At these stress levels the interaction of face sheet wrinkling with Euler buckling is imperfection sensitive. A graphical explanation of non-linear coupled instabilities can be given by a photo sequence and a force-axial shortening diagram of a sandwich panel loaded in compression (Figure 12). From the force-axial shortening diagram differences in the local and global buckling can be obtained in contrast to a force-out-of-plane deformation diagram where both modes will show similar buckling curves. To prevent coupled instabilities the compression stresses in the face sheets have to be lower than the wrinkling load of wrinkling case I – rigid base.
Figure 12: The photos and load-axial shortening graph show the loading sequence of an axial compressed sandwich panel [12]:
(1) Pre-buckling – path (a) on the graph;
(2) Euler buckling – path (b) and point C on the graph;
(3) Coupled instabilities leading to localization – path (c) on the graph;
Path (d) on the graph shows an imperfect sandwich panel response. The secondary bifurcation point is marked by \( S \) and the limit point of the imperfect geometry by \( l \).
The Greek symbol \( \varepsilon \) represents the initial imperfection in terms of the sandwich panel end-shortening.

2.5 FAILURE MECHANISMS

General failure modes of sandwich structures are failure of the face sheets by tension, compression, core failure, wrinkling of the compression face sheet, debonding at the core/face sheet interface, global buckling, and indentation failure under localized loading (Figure 13). The initiation and interaction of failure depends on geometry, type of loading and material properties. The failure modes mentioned in Figure 13 can be predicted by a complete stress analysis with respect to nonlinear and inelastic behaviour of constituent materials and interactions of failure modes. Stress analysis's have been derived for each failure mode and have been described in many publications [3], [8], [18], [35], [36].

Figure 13: Failure modes in sandwich panels: (a) Face yielding/fracture, (b) core shear failure, (c,d, and e) face wrinkling respectively case I rigid base, case II asymmetrical wrinkling, and case III symmetrical wrinkling, (f) global buckling, (g) shear crimping, (h) face dimpling, and (i) local indentation.
STABILITY OF AXIALLY LOADED GFRP SANDWICH WALL PANELS

a) Face yielding or fracture

Face yielding or fracture (a) has been discussed by Fleck et al. [3] as plastic micro-buckling of the face sheets. It occurs when the axial compressive stress within the face sheet exceeds the plastic micro-buckling strength $\sigma_{CR,P}$. Plastic micro-buckling strength is assumed as material property instead of a prediction of a micro-mechanical model. This strength strongly depends on the misalignment of fibres and shear strength of matrix. It leads to the overall collapse load (face sheet thickness $t$ and width $b$):

$$P = 2 \ t \ b \ \sigma_{CR,P}$$  \hspace{1cm} (V)

b) Core shear failure

Core shear failure will be assumed with classical beam theory [18]. The shear stress varies parabolic through the face sheet and core under 3-point bending. Because of differences in stiffness of the face sheet and core, the shear stress is taken linear through the face sheet and constant in the core (core thickness is $c$). The shear stress contribution of face sheets can be neglected. The shear stress will be taken into account by the core with:

$$P = 2 \ \tau_{CXZ} b \ (c + t)$$  \hspace{1cm} (VI)

Brittle failure will be assumed by exceeding the shear strength $\tau_{CS}$ of the core in similar direction. This means:

$$\tau_{CXZ} = \tau_{CS}$$  \hspace{1cm} (VII)

Core shear failure only occurs at eccentric loaded sandwich wall panels.

c) Face wrinkling case I Rigid base

Wrinkling models have been extensively discussed in subsection 2.4.2. The formulas of Allen are used to express critical wrinkling stresses at case I, II and III. Compression faces of sandwich panels can fail by a local instability mechanism named wrinkling. Local instability of the sandwich face consists of in-plane compression of the sandwich. This also applies when the sandwich is subjected to bending, because compression occurs in one of the face sheets. Allen [8] assumed the wavelength as the same order as the core thickness (Figure 14). Allen also developed a special theory to predict this behaviour by the differential equation method. It assumes a thin beam (face sheet) subjected to compressive end loads. This thin beam is continuously supported by an elastic medium (core) which extends infinitely at one side of the beam. The face is unaffected by the opposite face sheet.

$$P$$

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure14.png}
\caption{Wrinkling wave with wavelength ($l=L$)}
\end{figure}

The minimum critical stress at which wrinkling occurs is given by the following expression [34]:

$$\sigma_{z}$$
The constant $B_1$ depends on the wrinkling case c, d or e as mentioned in Figure 13. These cases are all assumed with isotropic core and face sheet materials. The face sheet bending modulus of elasticity $E_{FF}$ and core tensile modulus of elasticity $E_{TC}$ are included. This leads to $B_1$ of face wrinkling case I rigid base. $B_1$ may be taken as 0.575 for $\nu_C = 0.25$ in case of $\rho_r < 0.25$. The factor $\rho_r$ can be determined by:

$$\rho_r = \frac{t (E_{FF})^{1/3} \left( E_{TC} \right)^{1/3}}{C}$$

(IX)

If $\rho_r > 0.25$, then 0.575 for $B_1 = 0.575$ is an overestimation of the wrinkling stress.

d) Face wrinkling case II Asymmetrical wrinkling

Factor $B_1$ varies in each case. In case II $B_1$ may be taken as 0.58 for $\nu_C = 0.25$. More values of factor $B_1$ are found by Allen.

e) Face wrinkling case III Symmetrical wrinkling

Finally, $B_1$ is approximately 0.63 for $\rho_r < 0.25$. For larger values of $\rho_r$, $B_1 > 0.63$.

A more powerful formula of anisotropic face sheets and an isotropic core was also suggested by Allen for the natural wavelength and instability load of Figure 14:

$$L_w = \left( \frac{2 \pi^4 D_f}{a} \right)^{1/3}$$

(X)

$$a = \frac{2 \pi E_{TC}}{\left(3 - \nu_C \nu_C \right) \left(1 + \nu_C \right)} \text{, with tensile modulus of elasticity } E_{TC}$$

(XI)

$$P = \left( \frac{1}{2^{2/3} + 2^{1/3}} \right) \frac{1}{\pi^2} \left( D_f a^2 \right)^{1/3} \text{, with bending stiffness } D_f \text{ of the face sheet only.}$$

(XII)

f) Global buckling

The global buckling load $P_{CR}$ is not accurately predicted by the Euler buckling load ($P_E$) [3]. Euler buckling occurs at lower loads than shear buckling for slender structures. It is relevant to take the core shear buckling load ($P_S$) into account as well. This leads to a combined collapse load written as a reciprocal value:

$$\frac{1}{P_{CR}} = \frac{1}{P_E} + \frac{1}{P_S}$$

(XIII)

Sandwich panels with cores that have a very low shear modulus will be dominated by the term of the core shear buckling load [2]. The global buckling load converges to the value $P_S$. If the core shear modulus is very high (e.g., a honeycomb core), the global buckling load approaches the Euler buckling load $P_E$. The Euler buckling load can be written in terms of sandwich panel stiffness ($D_i$) and the critical buckling length $L_{CR}$:

$$P_E = \frac{\pi^2 D_i}{L_{CR}}$$

(XIV)
And the core shear buckling load is:

\[ P_S = (AG_c)_{EQ} = b (c + t) G_c \]  

(XV)

The equivalent shear rigidity \((AG_c)_{EQ}\) of the core is approximately the same as the shear modulus of the core \(G_c\) and the cross-sectional area \((A)\). The thickness value in this area \((A)\) is the distance between centre gravity lines of face sheets (i.e., \(c + t\)).

g) Shear crimping

Sandwich panels with a small shear rigidity compared to flexural rigidity and a relatively low length to thickness ratio will fail by a local instability called shear crimping. Shear crimping is sometimes referred to shear buckling and can be predicted by the formula of Engesser. Engesser’s formula fits really well to experimental results of Fleck and Sridhar [37]. Shear crimping, i.e., a localized material failure, occurs by exceeding the upper limit of Engesser’s buckling formula \(G_c A_m\) which is referred to the shear crimping load:

\[ P_{CR,S} = G_c A_m = \frac{G_c b}{c} (c + t)^2 \]  

(XVI)

h) Face dimpling

Face dimpling is a localized mode of failure that occurs in sandwich panels with discontinuous cores such as honeycomb or corrugated cores [36]. Between the cell walls of the core buckles the face sheet into cell cores. Face dimpling occurs in sandwich panels with relatively large cells and thin faces. Many of these buckles together can even lead to face wrinkling as buckling mode.

i) Local indentation

Sandwich panels subjected to out of plane loading can fail if the core under the face sheet starts yielding [38]. The compression strength of the core material is \(\sigma_{CC}\). The critical load \(P_{ca}\) at core yielding can be defined by:

\[ P_{CR,Y} = 1.70 \sigma_{CC} b t \left( \frac{E_{FF}}{E_{TC}} \right)^{1/3} \]  

(XVII)

2.6 CONCLUSIONS

- To predict characteristic properties of composites the fibre ratio, fibre type, resin type, fibre orientation and lamina structure are required [24]–[26].
- The compression modulus of elasticity is equal to the tensile modulus of elasticity in UD GFRP laminate.
- Regardless of open cell or closed cell foams the Poisson ratio can be approximated by 1/3.
- To prevent adhesive failure the shear strength and tensile strength must be larger than the core material.
- Bending behaviour of sandwich panels is described in the linear sandwich theory.
- The theory of Allen [8] distinguishes three types of wrinkling. The wrinkling formula neglects the contribution of the core shear modulus of elasticity and the complete sandwich panel length and width. Regardless of these missing properties Allen’s theory performs well to estimate the wrinkling behaviour.
- Failure mechanisms of individual geometric instabilities can be predicted according to section 2.5.
- Theories about geometric instabilities describe a single instability mechanism, but experimental validation of the instability mechanisms is rarely done [16]–[19].
3. EXPERIMENTAL TESTS

The discussed literature is used to perform experimental tests. The experimental tests were performed in the ‘Pieter van Musschenbroek’ laboratory of the Eindhoven University of Technology, where test equipment is available to execute several tests. The tests consist of two categories:

- Material tests;
- Sandwich panel tests.

Constituent materials of fibre reinforce composite (FRC) sandwich panels are glass fibre reinforced polymer (GFRP) woven fabric face sheets, adhesive, and extruded polystyrene (XPS). The adhesive between the XPS core material and GFRP face sheets of a sandwich panel has stronger material properties than the XPS. Failure occurs in the XPS rather than in the glue. Experimental tests to determine material properties of the sandwich panel only require tests on the XPS and GFRP material:

- Test type 1: GFRP tensile properties;
- Test type 2: XPS shear properties;
- Test type 3: XPS compression properties;
- Test type 4: XPS tensile properties.

The experimental tests on sandwich panels to examine buckling contain two test types:

- Test type 5: Load introduction cubic sandwich panel;
- Test type 6: Instability sandwich panel.

3.1 SANDWICH PANEL TYPE AND TEST CONDITIONS

A Dutch manufacturing company 'Baer BV' constructs sandwich panels by a vacuum-assisted resin transfer moulding (VARTM) technique (Figure 15). It is the most common moulding technique applied to the process of vacuum infusion. Sandwich panels are moulded by use of face sheets and core material with resin in a vacuum process. Outer atmospheric pressure compresses face sheet material tight against the core material. The resin is used as adhesive between face sheet and core material. The adhesive is a poly urethane consisting of a two part adhesive thermoset. It has a tensile strength of 12 MPa and a shear strength of 10 MPa.
The sandwich panels consist of two woven fabric glass fibre reinforced polymer (GFRP) face sheets with a XPS core material in between. Face sheets of GFRP thermosets have a maximum thickness of 3,0 mm. To compare failure behaviour of different sandwich panels the thickness of face sheets varies from 0,8 up to 3,0 mm. Sandwich panel material properties depend on limitations set by the supplier and production costs. The face sheet material is an orthotropic GFRP with fibre directions into zero and 90 degrees, named woven fabric. Woven fabric materials consist of a main fibre direction and secondary fibre direction perpendicular to the main fibre direction. A polymer resin surrounds the glass fibres of the face sheet. The face sheet material has an orthotropic non-linear elastic GFRP woven fabric with a thickness of 0,8 or 1,5 or 3,0 mm. The two important aspects of the sandwich panel core material are the shear stress and shear modulus of elasticity. The core material XPS and honeycomb perform better on these aspects than extruded poly styrene (EPS). XPS is less expensive than a honeycomb core and therefore XPS as core material is appropriate to use. The core material thickness in a sandwich panel depends on the requirements of the minimum thermal conductivity level (Rc value) in The Netherlands. Since January 2015 is the Rc value 5,0 m²K/W and leads to a core material thickness of 150 mm.

The Dutch building Standard ‘Bouwbesluit 2012’ of the built environment determines the height of the sandwich panel. The minimum requirements of the height from the top side of the floor till the bottom side of the next floor leads to a sandwich panel height of 2650 mm. The sandwich wall panel is to be used as a load bearing element in a structure. The sandwich panel only has to carry compression forces from above. The assumption of the width to height ratio of 1:3 results in a sandwich panel width of 900 mm. The sandwich panel geometry has dimensions of 900 x 2650 x 150 mm (width x height x thickness) with a GFRP face sheet thickness of 0,8 mm or 1,5 mm or 3 mm.

Test Standards are available for each characteristic property test in contrast to sandwich panel tests. Tests of characteristic properties comply with European test Standards. The following test Standards are used to test material properties:

3.2 STATISTICS

The average stress at failure is equal to an estimate sample mean ($\bar{x}$) from a group of observations (n). The estimate sample mean is an estimate of the population mean ($\mu$) by equation:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$  \hspace{1cm} (XVIII)

Formula (XIX) represents the estimate standard deviation (Sd):

$$S_d = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$  \hspace{1cm} (XIX)

The sample boundaries, i.e. lower bound (2.5%) and upper bound (97.5%), describe an area of 95% under a normal curve. The lower and upper bound values in a normal distribution lies within the approximate value of 1.96 times the estimate standard deviation of the mean. Using these statistical values result in a normal distribution of a specific sample with a 95% confidence interval within an area of $\bar{x} \pm 1.96 S_d$.

The shape of a normal distribution depends on the kurtosis and skewness [44]. The kurtosis, the first parameter, quantifies the degree to which a normal distribution has a peak. A normal distribution or Gaussian distribution has a kurtosis of zero. The minimum value is minus three and describes a flat shaped distribution, while a positive (infinite) value of the kurtosis refers to the peak shaped distribution. The second parameter, skewness represents asymmetry of a normal distribution. A negative value quantifies a negative skew with a long tail to the left and a positive value indicates a positive skew with a long tail to the right. A symmetrical distribution has a skewness of zero while a skewness larger than 1.0 or smaller than -1.0 is far from symmetrical. The kurtosis as well as the skewness is unitless.
3.3 TEST TYPE 1: GFRP TENSILE PROPERTIES

A deformation controlled tensile test on orthotropic GFRP determines the material properties according to the NEN-EN-ISO 527-1 (2012) [40] and NEN-EN-ISO 527-4 (1997) [41]. A testing machine of 250 kN exerts a tension force over the centre line of the GFRP woven fabric specimen by a constant test speed of 0,8 mm/min (Appendix A and figure 16). The orthotropic GFRP specimen has two fibre material directions, i.e. a longitudinal and transverse fibre direction.

The testing machine wedge action grips clamp the specimen at the top and bottom. While the wedge shaped grips clamp the specimen or while centring the specimen, the testing machine keeps the occurring pre-stress in the longitudinal direction of the specimen under a value of 25 N. This small pre-stress avoids a toe region in the first part of the stress-strain diagram.

The GFRP has three different material thicknesses according to the geometry groups specified in table 2 with each eight specimens. The width (w), thickness (t), and length (L) given in table 2 are specimen centre line dimensions. The total length of a specimen is 350 mm. Each group of specimens contains data of the tensile stress and longitudinal strain. Two specimens per group include an extra measurement of the transverse strain to indicate the poison ratio of the three groups. The GFRP specimens are cut from a single strip and not obtained from the sandwich panels of test type 6.
Table 2: Geometry sets specimens according to type 2 of the test standard [41].

<table>
<thead>
<tr>
<th>Name</th>
<th>Specimen number</th>
<th>02</th>
<th>03</th>
<th>04</th>
<th>05</th>
<th>06</th>
<th>07</th>
<th>08</th>
<th>09</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,0 mm</td>
<td></td>
<td>2,89</td>
<td>2,93</td>
<td>3</td>
<td>2,89</td>
<td>2,96</td>
<td>2,90</td>
<td>2,86</td>
<td>2,86</td>
<td>2,91</td>
</tr>
<tr>
<td></td>
<td>t [ mm ]</td>
<td>25,54</td>
<td>25,41</td>
<td>25,52</td>
<td>25,51</td>
<td>25,47</td>
<td>25,42</td>
<td>25,52</td>
<td>25,52</td>
<td>25,49</td>
</tr>
<tr>
<td></td>
<td>w [ mm ]</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>162</td>
<td>161</td>
<td>152,88</td>
</tr>
<tr>
<td>1,5 mm</td>
<td></td>
<td>2,49</td>
<td>2,52</td>
<td>2,51</td>
<td>2,54</td>
<td>2,51</td>
<td>2,47</td>
<td>2,53</td>
<td>2,53</td>
<td>2,50</td>
</tr>
<tr>
<td></td>
<td>t [ mm ]</td>
<td>25,31</td>
<td>25,36</td>
<td>25,35</td>
<td>25,35</td>
<td>25,39</td>
<td>25,39</td>
<td>25,49</td>
<td>25,38</td>
<td>25,38</td>
</tr>
<tr>
<td></td>
<td>w [ mm ]</td>
<td>158</td>
<td>157</td>
<td>157</td>
<td>157</td>
<td>157</td>
<td>157</td>
<td>157</td>
<td>157</td>
<td>157,13</td>
</tr>
<tr>
<td>0,8 mm</td>
<td></td>
<td>0,86</td>
<td>0,88</td>
<td>0,89</td>
<td>0,89</td>
<td>0,86</td>
<td>0,86</td>
<td>0,89</td>
<td>0,88</td>
<td>0,88</td>
</tr>
<tr>
<td></td>
<td>t [ mm ]</td>
<td>25,46</td>
<td>25,32</td>
<td>25,53</td>
<td>25,37</td>
<td>25,46</td>
<td>25,28</td>
<td>25,32</td>
<td>25,16</td>
<td>25,36</td>
</tr>
<tr>
<td></td>
<td>w [ mm ]</td>
<td>157</td>
<td>157</td>
<td>157</td>
<td>157</td>
<td>157</td>
<td>157</td>
<td>157</td>
<td>157</td>
<td>157</td>
</tr>
</tbody>
</table>

The tensile test on the GFRP specimens uses a single side strain-testing method. The ratio of the stress over the longitudinal strain between the values of $\varepsilon' = 0,005$ to $\varepsilon'' = 0,0025$ results in the tensile modulus of elasticity [40]. The dashed line in a stress-strain diagram of figure 17, Figure 18 and Figure 19 represents this modulus of elasticity. The AVE measures the longitudinal strain over a gauge length of 80 mm. To determine the poison ratio the transverse strain is needed. A foil strain gauge (FLK-6-11) with a length of 6 mm measures the transverse strain with a strain limit of two percent. The position of the strain gauge is at the surface contrary to the surface of the longitudinal strain measurement at the middle of the specimen length. The region of the longitudinal strain of $\varepsilon' = 0,003$ to $\varepsilon'' = 0,015$ is valid to calculate the ratio of the transverse strain over the longitudinal strain resulting in the poison ratio [40]. As well as the data to determine the tensile modulus of elasticity as the data to determine the poison ratio satisfy a correlation coefficient of at least 0,99 ($R^2$-value).

Appendix A contains test results of individual specimens of the GFRP face sheet tensile test. Figure 17 represents the engineering stress to engineering strain relation of the GFRP face sheet material with a thickness of 0,8 mm. The material behaviour of the face sheet in longitudinal fibre direction as well as the transverse fibre direction is linear elastic to 30 MPa and then non-linear elastic until tensile failure suddenly occurs.
A crack in test specimen 48 near the top grips of the testing machine rejects this specimen from determining the average tensile strength and average ultimate strain. However, before the crack arises test specimen 48 is useful to determine the average tensile modulus of elasticity and average poison ratio. The specimen with the lowest engineering strain at failure determines the thick black vertical line of the normal distribution (Figure 17) and therefore the mean value of the engineering stress. The statistical values of table 3 represent the material properties of 0,8 mm GFRP face sheet and show a small deviation between the specimens. The kurtosis nearby zero indicates good agreements to a Gaussian distribution with a long tail to the left marked by the skewness of almost minus one.

Table 3: Average tensile values of 0,8 mm GFRP face sheet

<table>
<thead>
<tr>
<th>GFRP 0,8 mm tensile properties</th>
<th>Unit</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength, mean ($\sigma_u \bar{x}$)</td>
<td>134 [ MPa ]</td>
<td></td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>1,646 [%]</td>
<td></td>
</tr>
<tr>
<td>Modulus of elasticity ($E$)</td>
<td>9924 [ MPa ]</td>
<td></td>
</tr>
<tr>
<td>Poison ratio</td>
<td>0,37 [-]</td>
<td></td>
</tr>
<tr>
<td>Standard deviation ($Sd$)</td>
<td>2,7 [ MPa ]</td>
<td></td>
</tr>
<tr>
<td>2,5% lower bound</td>
<td>128,8 [ MPa ]</td>
<td></td>
</tr>
<tr>
<td>97,5% upper bound</td>
<td>139,5 [ MPa ]</td>
<td></td>
</tr>
<tr>
<td>Kurtosis</td>
<td>-0,27 [-]</td>
<td></td>
</tr>
<tr>
<td>Skewness</td>
<td>-0,79 [-]</td>
<td></td>
</tr>
</tbody>
</table>
Figure 18 shows the specimens with a face sheet thickness of 1.5 mm. The material behaviour of the longitudinal fibre direction as well as the transverse fibre direction is linear elastic to 20 MPa and then non-linear elastic until tensile failure suddenly occurs. Failure occurs at most of the specimens in the middle of the height.

![Graph showing stress-strain behavior of GFRP 1.5 mm](image)

**Figure 18:** Left: Average tensile test GFRP 1.5 mm. Right: Location of failure.

A crack in test specimen 24 near the bottom grips of the testing machine rejects this specimen from determining the average tensile strength and average ultimate strain. However, before the crack arises test specimen 24 is useful to determine the average tensile modulus of elasticity. The statistical values of table 4 represent the average test results of 1,5 mm GFRP face sheet. The standard deviation is small. The kurtosis indicates a peaked shape distribution and the skewness value larger than one indicates a skew distribution with a long tail to the right which is far from symmetrical.

**Table 4:** Average tensile values of 1,5 mm GFRP face sheet

<table>
<thead>
<tr>
<th>GFRP 1,5 mm tensile properties</th>
<th>Unit</th>
<th>80</th>
<th>85</th>
<th>89</th>
<th>97,5%</th>
<th>2,5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength, mean (σu, x)</td>
<td>MPa</td>
<td>80</td>
<td>85</td>
<td>89</td>
<td>97,5%</td>
<td>2,5%</td>
</tr>
<tr>
<td>Strain at failure (εu)</td>
<td>%</td>
<td>1,280</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus of elasticity (E)</td>
<td>MPa</td>
<td>7218</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poison ratio</td>
<td></td>
<td>0,10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation (Sd)</td>
<td>MPa</td>
<td>3,5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,5% lower bound</td>
<td>MPa</td>
<td>73,5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>97,5% upper bound</td>
<td>MPa</td>
<td>87,4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kurtosis</td>
<td></td>
<td>4,62</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skewness</td>
<td></td>
<td>1,96</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 19 contains the results of a 3 mm GFRP face sheet. The material behaviour of the longitudinal fibre direction is linear elastic up to 20 MPa. From 20 MPa to 45 MPa the lines are far from straight but rather a little coarse. The material behaviour is non-linear elastic and the slope of the engineering stress to engineering strain decreases around 45 MPa. Tensile failure of most of the specimens occur at a strain of 1.2 %. On the other hand, the engineering stress to engineering strain of the transverse fibre direction remains linear elastic up to small tensile cracks arise.

A crack in test specimen 06 and 08 near the bottom grips of the testing machine rejects these specimens from determining the average tensile strength and average ultimate strain. However, before the crack arises test specimen 06 and 08 are useful to determine the average tensile modulus of elasticity. The statistical values of table 5 show the average test results of 3 mm GFRP face sheet with a small standard deviation between the results. The kurtosis shows a peaked shape distribution. The distribution is near symmetrical due to an almost zero skewness.

Table 5: Average tensile values of 3 mm GFRP face sheet

<table>
<thead>
<tr>
<th>GFRP 3 mm tensile properties</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength, mean (σ_u, x)</td>
<td>55 [ MPa ]</td>
</tr>
<tr>
<td>Strain at failure (ε_u)</td>
<td>0,996 [% ]</td>
</tr>
<tr>
<td>Modulus of elasticity (E)</td>
<td>6679 [ MPa ]</td>
</tr>
<tr>
<td>Poison ratio</td>
<td>0,27 [- ]</td>
</tr>
<tr>
<td>Standard deviation (Sd)</td>
<td>2,2 [ MPa ]</td>
</tr>
<tr>
<td>2,5% lower bound</td>
<td>50,4 [ MPa ]</td>
</tr>
<tr>
<td>97,5% upper bound</td>
<td>59,0 [ MPa ]</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>1,74 [- ]</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0,13 [- ]</td>
</tr>
</tbody>
</table>

Figure 19: Left: Average tensile test GFRP 3,0 mm. Right: Location of failure.
The discussion about the GFRP face sheets threat a few notable aspects by the failure mechanism, stress-strain diagram, poison ratio, and the statistical meaning of the results.

The sudden breakage of the specimen indicates failure by exceeding the tensile strength of the GFRP face sheet. In spite of the specimen thickness or lamina structure, the failure mechanism of the GFRP face sheet is similar at each test (Figure 20). At failure, the longitudinal fibres of the woven fabric break and the transverse fibres remain intact. It is obvious by comparing the small strains of the transverse fibre direction to the large strains of the longitudinal fibre direction.

![Figure 20: Failure of GFRP face sheets from left to right: 0.8 mm, 1.5 mm and 3 mm. Middle: The red line indicates the length of a 6 mm foil strain gauge over three fibre bundles. The square gridlines are 5 x 5 mm.](image)

While the GFRP face sheet thickness increases, the glass content of the fibres decreases, and therefore the strength and stiffness decrease. The material behaviour of the first part of the stress-strain diagrams is linear elastic. The second part is non-linear elastic. In the non-linear elastic part at 2/3 of the ultimate engineering stress a warning mechanism occurs by a hearable sound of breaking glass fibres during the test. This process continues until the material fails. By looking close to the lines that describe the longitudinal fibre direction of the stress-strain diagrams, coarse lines are visible. This occurs due to the frictional resistance of the longitudinal fibres to the transverse fibre direction. The friction between the fibres interrupts the longitudinal fibre from elongation and results in a coarse line.

The poison ratio of 0.37 or 0.10 or 0.27 has a large variation at a face sheet thickness of respectively 0.8 mm or 1.5 mm or 3 mm. The transverse strain measurement strongly influence these values. The strain gauge to measure the transverse strain has a length of 6 mm. A bundle fibres in either the transverse or longitudinal has a width of 3 mm. The location of the strain gauge over a bundle of two or three is very important as can be seen in figure 20. Therefore, a foil strain gauge of 6 mm is too short to exactly determine the poison ratio. The statistical meaning of the transverse engineering strain to determine the poison ratio is only an indication of what the poison ratio might be. By performing a measurement of at least five specimens the material property has a statistical meaning as can be seen at the measurement of the engineering stress and longitudinal engineering strain.

The statistical values differ per material thickness. Small standard deviations of the engineering stress, a kurtosis with a higher value than one (peaked shape normal distribution), and small variations of the skewness indicate the relative constant quality of an engineered material in contrary to a material of nature, like timber which has larger variations.
3.4 TEST TYPE 2: XPS SHEAR PROPERTIES

The ISO Standard 1922 [42] describes a deformation controlled shear test to define the shear strength and shear modulus of rigid cellular plastics, like the XPS core material. A sandwich test specimen hangs vertical between two fixing devices. The bottom device remains fixed to the specimen while the fixing device at the top attached to the testing machine, can move along the longitudinal axis of the specimen. A testing machine of 100 kN exerts a tension force (Figure 21) via the steel plates into the sandwich test specimen by a constant test speed of 0,8 mm/min. Two roller supports at both sides of the steel plates prevent the specimen from bending caused by the tension force into the eccentric placed steel plates. The steel plates transfer the tension force into a shear stress acting along a parallel direction to the longitudinal axis of the XPS specimen. During the test, a 100 kN load cell measures the acting force with an accuracy of 0,001 kN (class 1).

![Figure 21: Left: Test setup. Middle top: Steel plates with roller supports. Right: Technical drawing. Middle bottom: Shear deformation.](image)

The specimen geometry consist of a sandwich panel with GFRP face sheets with a thickness of 3,0 mm and a XPS core material with a thickness of 25 mm (Appendix B and table 6). The sandwich panel manufacturing company (BAER bv Sandwich panels) is able to construct an adhesive bond between the XPS surface and the GFRP face sheet. The bond connection between the specimens face sheet and steel plate can be achieved in the laboratory by a two component epoxy adhesive (Permacol 2205 A/B). The glue used for bonding the face sheet to the steel strip is inappropriate to use for fixing the LVDT (linear variable differential transformer) to the surface of the XPS core material. The LVDT has to measure the longitudinal deformation of the XPS during the test. Therefore, by neglecting the deformations of the glue and GFRP face sheets, the LVDT (Solartron AX/10/S) measures the longitudinal
deformation between the steel plates with an accuracy of 10 μm over a gauge length of 160 mm with a range of ±10 mm. The XPS is cut from a single plate and not obtained from the sandwich panels of test type 6.

Table 6: Geometry test specimens

<table>
<thead>
<tr>
<th>Name</th>
<th>b1 [ mm ]</th>
<th>b2 [ mm ]</th>
<th>d1 [ mm ]</th>
<th>d2 [ mm ]</th>
<th>L1 [ mm ]</th>
<th>L2 [ mm ]</th>
<th>Steel bottom [ N ]</th>
<th>Steel top [ N ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>G01</td>
<td>50,06</td>
<td>50,06</td>
<td>24,96</td>
<td>24,97</td>
<td>246</td>
<td>247</td>
<td>46,640</td>
<td>46,652</td>
</tr>
<tr>
<td>G02</td>
<td>50,02</td>
<td>50,08</td>
<td>24,89</td>
<td>24,98</td>
<td>249</td>
<td>250</td>
<td>46,440</td>
<td>46,542</td>
</tr>
<tr>
<td>G03</td>
<td>50,00</td>
<td>50,02</td>
<td>24,97</td>
<td>25,03</td>
<td>249</td>
<td>249</td>
<td>46,450</td>
<td>46,592</td>
</tr>
<tr>
<td>G04</td>
<td>49,99</td>
<td>50,07</td>
<td>24,97</td>
<td>24,90</td>
<td>250</td>
<td>249</td>
<td>46,500</td>
<td>46,652</td>
</tr>
<tr>
<td>G05</td>
<td>50,05</td>
<td>50,06</td>
<td>24,97</td>
<td>25,02</td>
<td>247</td>
<td>247</td>
<td>46,460</td>
<td>46,702</td>
</tr>
</tbody>
</table>

It is important to emphasize the procedure to derive the actual load applied into the specimen. The weight of the specimen itself (face sheet, core material, and face sheet) is negligible small compared to the measured force of the load cell, weight of steel parts and pre-stress. The data from the load cell must be corrected for a part of the self-weight of the steel parts (plates, block A and B, screws). The load cell does not measure all the force transferred by shear through the specimen. Hence, an additional load of 82N must be accounted for in the results of the test. The lower steel parts (Table 6, steel bottom) and the applied prestress are loading the specimen before the data recording starts.

To perform a deformation controlled shear test within an appropriate time the test speed varies during the test with a variation less than ten percent during the test. The initial speed of 0,5 mm/min in the linear elastic branch of the force-deformation diagram changes to 1,0 mm/min by reaching the plastic branch in the force-deformation diagram. At a deformation of five millimetres the test speed increases to 1,5 mm/min until failure of the XPS. Failure occurs by exceeding the shear strength of the XPS (Figure 22).

Figure 22: Left and middle: XPS shear failure due to exceeding the tensile strength at the corners of the XPS core material. Shear failure at the middle of the height of the XPS core material.
Failure of four specimen starts in the corner of the XPS core material where peak shear stresses arise. One specimen shows small shear cracks at failure (Figure 22, right photo). The cracks grow until the XPS core material is unable to resist a higher shear stress and the XPS core material fails. The cracks in the XPS core material of figure 22 occur all outside the range of 0,1 $F_{\text{max}}$ to 0,4 $F_{\text{max}}$. This range can be recognised by a dashed blue line that marks the slope of the force-deformation diagram (Figure 23). This range represents the linear elastic branch in the force-deformation diagram with a correlation coefficient of at least 0,99 ($R^2$-value) to derive the shear modulus of elasticity of the XPS. The measure equipment of specimen G04 in figure 23 was beyond limits and stopped to collect any data. However, the linear part of the graph is usable to derive the shear modulus of elasticity.

![Test speed increases from 0,5 to 1,0 mm/min and from 1,0 to 1,5 mm/min](image)

The specimens represent exact the same behaviour in the linear part of the force-deformation diagram. When the shear modulus of the XPS material decreases, becomes the relation non-linear between the force and the deformation. At a level of 4,5 KN the XPS has a plastic material behaviour until failure occurs. In table 7, a very small standard deviation, a kurtosis higher than one and a small skewness indicate small variations to an engineered material. Appendix B shows individual test results.

Table 7: Average shear values XPS core material

<table>
<thead>
<tr>
<th>XPS shear properties</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear strength, mean ($\tau$, $\mu$)</td>
<td>0,489 [ MPa ]</td>
</tr>
<tr>
<td>Shear modulus of elasticity ($G$)</td>
<td>10,4 [ MPa ]</td>
</tr>
<tr>
<td>Standard deviation ($Sd$)</td>
<td>0,184 [ kN ]</td>
</tr>
<tr>
<td>2,5% lower bound</td>
<td>5,535 [ kN ]</td>
</tr>
<tr>
<td>97,5% upper bound</td>
<td>6,259 [ kN ]</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>2,75 [ - ]</td>
</tr>
<tr>
<td>Skewness</td>
<td>1,59 [ - ]</td>
</tr>
</tbody>
</table>
### 3.5 TEST TYPE 3: XPS COMPRESSION PROPERTIES

A 250 kN testing machine exerts a compression force with a test speed of 0.6 mm/min (deformation controlled test) via a ball joint of 153 grams and square steel plate of 177 grams into the top of a rectangular geometry (Table 8) of XPS material (figure 24). The dead load of the ball joint and square steel plate leads to a small prestress in the XPS material. This applied prestress is added to the recorded data of the applied force of the testing machine to determine the total stress.

![Test setup and technical drawing](image)

Figure 24: Left: Test setup (The pink colour refers to the light used by the advanced video extensometer). Right: Technical drawing.

The measure equipment of the testing machine measures the applied force and strain at an interval of 0.1 seconds by respectively a 5 kN load cell and an advanced video extensometer (AVE 2663-821). The load cell has an accuracy of 0.025 N (class 0.5) and the AVE measures the longitudinal strain over a gauge length of 25 mm with an accuracy of ± 2.5 μm (class 0.5). If the specimen is loaded by compression, all four sides of the specimen are able to deform free in lateral direction due to teflon layers at the bottom and top side of the specimen. The XPS is cut from a single plate and not obtained from the sandwich panels of test type 6.

<table>
<thead>
<tr>
<th>Name</th>
<th>b1 [mm]</th>
<th>b2 [mm]</th>
<th>b3 [mm]</th>
<th>b4 [mm]</th>
<th>h1 [mm]</th>
<th>h2 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>E4-00</td>
<td>25,00</td>
<td>25,00</td>
<td>25,00</td>
<td>25,00</td>
<td>50,00</td>
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<tr>
<td>E4-01</td>
<td>25,25</td>
<td>25,55</td>
<td>25,19</td>
<td>25,19</td>
<td>50,84</td>
<td>52,21</td>
</tr>
<tr>
<td>E4-02</td>
<td>25,09</td>
<td>25,26</td>
<td>25,10</td>
<td>25,12</td>
<td>50,38</td>
<td>50,38</td>
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<td>E4-03</td>
<td>25,19</td>
<td>25,19</td>
<td>25,22</td>
<td>25,13</td>
<td>50,35</td>
<td>50,42</td>
</tr>
<tr>
<td>E4-04</td>
<td>25,25</td>
<td>25,12</td>
<td>25,79</td>
<td>25,11</td>
<td>50,41</td>
<td>50,41</td>
</tr>
<tr>
<td>E4-05</td>
<td>25,00</td>
<td>25,00</td>
<td>25,06</td>
<td>25,17</td>
<td>50,36</td>
<td>50,43</td>
</tr>
<tr>
<td>E4-06</td>
<td>25,21</td>
<td>25,20</td>
<td>25,30</td>
<td>25,60</td>
<td>50,38</td>
<td>50,41</td>
</tr>
<tr>
<td>E4-07</td>
<td>24,86</td>
<td>25,11</td>
<td>25,16</td>
<td>25,15</td>
<td>50,38</td>
<td>50,41</td>
</tr>
<tr>
<td>E4-08</td>
<td>25,62</td>
<td>25,41</td>
<td>25,18</td>
<td>25,18</td>
<td>50,29</td>
<td>50,27</td>
</tr>
<tr>
<td>E4-09</td>
<td>25,63</td>
<td>25,73</td>
<td>25,25</td>
<td>25,19</td>
<td>50,42</td>
<td>50,34</td>
</tr>
<tr>
<td>E4-10</td>
<td>25,09</td>
<td>25,17</td>
<td>24,91</td>
<td>25,15</td>
<td>50,41</td>
<td>50,41</td>
</tr>
<tr>
<td>E4-11</td>
<td>25,53</td>
<td>25,64</td>
<td>25,18</td>
<td>25,26</td>
<td>50,34</td>
<td>50,18</td>
</tr>
</tbody>
</table>

Table 8: Geometry test specimens

---

g = gauge length of 25 mm
The linear branch of the stress-strain diagram (dashed line in figure 25) between the values of \(\varepsilon' = 0,0005\) to \(\varepsilon'' = 0,0025\%\) describes the initial compression modulus of elasticity. The slope of the linear branch satisfies a correlation coefficient of at least 0,99 (\(R^2\)-value). The material behaviour is non-linear elastic up to failure occurs. A cross sign in the graph indicates the ultimate load. Failure of the XPS micro structure is invisible and can only be recognised during the test in the stress-strain diagram due to a decreasing stress after reaching the ultimate stress.

![Figure 25: Average compression results test E4. After reaching the ultimate load (cross sign) the tests are halted manually.](image)

Appendix C contains the individual test results. The accuracy of the measure equipment has been examined by performing an initial test ‘E4-00’ with a geometry of 25 x 25 x 50 mm (width x depth x height). The assumed dimensions of the initial test E4-00 and skew geometry of test E4-01 and E4-10 reject these three specimens from determining the average compression values (Table 9). The small standard deviation, kurtosis and skewness indicate a well-engineered material.

Table 9: Average compression values XPS material

<table>
<thead>
<tr>
<th>XPS compression properties</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression strength, mean (\sigma_u)</td>
<td>0,404  [ MPa ]</td>
</tr>
<tr>
<td>Engineering strain at failure (\varepsilon_u)</td>
<td>2,287  [ % ]</td>
</tr>
<tr>
<td>Initial modulus of elasticity (E)</td>
<td>30,3   [ MPa ]</td>
</tr>
<tr>
<td>Standard deviation (Sd)</td>
<td>0,011  [ MPa ]</td>
</tr>
<tr>
<td>2,5% lower bound</td>
<td>0,381  [ MPa ]</td>
</tr>
<tr>
<td>97,5% upper bound</td>
<td>0,427  [ MPa ]</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>0,81   [- ]</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0,32  [- ]</td>
</tr>
</tbody>
</table>
3.6 TEST TYPE 4: XPS TENSILE PROPERTIES

Two geometries and two types of measure equipment are used to find the optimal conditions to perform a XPS tension test. Firstly, a rectangular prism fails at the gripping jaws of the test machine due to necking of the material. A dog bone shaped test piece leads to better results. Secondly, the advanced video extensometer (AVE) is able to measure the compressive strain in contrary to strain gauges attached with glue. The XPS material dissolve at the bond layer. A 250 kN testing machine exerts a tension force with a test speed of 0,6 mm/min (deformation controlled test) onto the symmetric dog bone shaped specimen with a thickness \( b_2 \) as specified in Appendix D and figure 26. The XPS is cut from a single plate and not obtained from the sandwich panels of test type 6.

<table>
<thead>
<tr>
<th>Name</th>
<th>( b_1 ) [mm]</th>
<th>( b_2 ) * [mm]</th>
<th>( L ) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>E5-00</td>
<td>24,64</td>
<td>25,22</td>
<td>170,00</td>
</tr>
<tr>
<td>E5-01</td>
<td>24,95</td>
<td>25,08</td>
<td>169,00</td>
</tr>
<tr>
<td>E5-02</td>
<td>24,96</td>
<td>25,10</td>
<td>170,00</td>
</tr>
<tr>
<td>E5-03</td>
<td>25,17</td>
<td>25,26</td>
<td>169,00</td>
</tr>
<tr>
<td>E5-04</td>
<td>24,98</td>
<td>25,20</td>
<td>170,00</td>
</tr>
<tr>
<td>E5-05</td>
<td>25,39</td>
<td>24,85</td>
<td>170,00</td>
</tr>
<tr>
<td>E5-06</td>
<td>24,96</td>
<td>25,10</td>
<td>169,00</td>
</tr>
</tbody>
</table>

* thickness specimen

\( g = \) gauge length of 80 mm

Figure 26: Test setup (pink colour refers to the extensometer light) and geometry specimen.

The testing machine wedge action grips clamp the specimen at the top and bottom. The measure equipment of the testing machine measures the applied force and strain at an interval of 0,1 seconds by respectively a 250 kN load cell and an advanced video extensometer (AVE 2663-821). The load cell has an accuracy of 1,25 N (class 0,5) and the AVE measures the longitudinal strain over a gauge length of 80 mm with an accuracy of ± 2,5 μm (class 0,5).

In the stress-strain diagram of figure 27 the material behaviour is up to 0,4 MPa linear elastic. The tensile modulus of elasticity describes the slope of the linear branch of the stress-strain diagram in figure 27 by the ratio of the stress over the strain with a minimum correlation coefficient \( R^2 \) value of 0,99. All test specimens are valid to use for the tensile modulus of elasticity. However, specimen E5-04 breaks between the grips and the gauge mark and therefore specimen E5-04 is invalid to use for determining the average stress and strain values (Table 10). After 0,4 MPa the material behaviour is non-linear elastic until the XPS material fails by exceeding the tensile strength. By reaching the tensile strength, the XPS material also reaches a large engineering strain. The specimen breaks into two separate parts at the middle of the length of the specimen. The individual results of the XPS tensile test are given in Appendix D.
Figure 27: Average tensile results test E5. The cross signs in the diagram represent failure.

A very small standard deviation, a small kurtosis and a skewness near to zero indicate a well-engineered material with small variations between six specimens. By comparing the compression strength and compression engineering strain at failure of section 3.5 to the tensile strength and tensile engineering strain at failure of section 3.6, can be seen that the tensile strength and tensile engineering strain at failure are higher by almost a factor two. This large deviation of material properties in compression compared to tension can be attributed to the micro structure of the XPS material.

Table 10: Average tensile values

<table>
<thead>
<tr>
<th>XPS tensile properties</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength, mean (σ_u, μ)</td>
<td>0.715 [MPa]</td>
</tr>
</tbody>
</table>
3.7 TEST TYPE 5: LOAD INTRODUCTION CUBIC SANDWICH PANEL

The main objective is to examine the load introduction conditions at the top edge of the sandwich panel and to give an indication of the compression properties of the GFRP face sheets. A 250 kN testing machine applies a uniaxial compression force into a cubic sandwich panel specimen with a test speed of 0,2 mm/min by a deformation controlled test (Figure 28). During the test a 250 kN load cell measures the acting force with an accuracy of 0,0025 kN. The specimen geometry varies by differ the GFRP face sheet thickness to examine the load introduction conditions at the top edge of the specimen. The face sheet thickness categorise the specimens into three groups of 0,8 mm, 1,5 mm and 3 mm. The dimensions of the XPS remains constant 150 mm at each geometry configuration of table 11.

![Figure 28: Left: test setup. Top right: Technical drawing. Bottom right: Measure equipment.](image)

As showed in figure 28, the LVDT's (Solartron AX/10/S) have an accuracy of 10 μm and a range of ±10 mm measure the axial shortening and lateral displacements of the specimen. By neglecting possible deformations of the steel section two LVDT's measure the axial shortening over the total height of a specimen. Two LVDT's measure the lateral deformations in the middle of the specimen at the face sheet surface at a height of 40 mm from the top edge (see location LVDT in Appendix E). Two specimens per group include a strain gauge to measure the axial strain to indicate a value of the compression modulus of elasticity. A single sided polyester foil strain gauge (PFL-20-11) with a length of 20 mm measures the axial strain until a strain limit of two percent.
Table 11: Geometry test specimens

<table>
<thead>
<tr>
<th>Name</th>
<th>b   [ mm ]</th>
<th>h1  [ mm ]</th>
<th>h2  [ mm ]</th>
<th>L1  [ mm ]</th>
<th>L2  [ mm ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,0 mm face sheet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S4-05</td>
<td>156,00</td>
<td>149,40</td>
<td>150,26</td>
<td>149,77</td>
<td>149,00</td>
</tr>
<tr>
<td>S4-06</td>
<td>156,00</td>
<td>149,00</td>
<td>149,10</td>
<td>149,44</td>
<td>149,40</td>
</tr>
<tr>
<td>S4-07</td>
<td>156,00</td>
<td>150,73</td>
<td>150,94</td>
<td>148,96</td>
<td>149,25</td>
</tr>
<tr>
<td>S4-08</td>
<td>156,00</td>
<td>148,94</td>
<td>148,73</td>
<td>149,03</td>
<td>149,35</td>
</tr>
<tr>
<td>S4-09</td>
<td>156,00</td>
<td>150,70</td>
<td>150,74</td>
<td>149,01</td>
<td>149,19</td>
</tr>
<tr>
<td>S4-10</td>
<td>156,00</td>
<td>150,65</td>
<td>151,77</td>
<td>149,60</td>
<td>148,93</td>
</tr>
<tr>
<td>Average</td>
<td>156,00</td>
<td>150,08</td>
<td></td>
<td></td>
<td>149,24</td>
</tr>
<tr>
<td>1,5 mm face sheet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S4-20</td>
<td>153,52</td>
<td>149,79</td>
<td>149,73</td>
<td>148,44</td>
<td>149,46</td>
</tr>
<tr>
<td>S4-21</td>
<td>153,59</td>
<td>150,14</td>
<td>151,08</td>
<td>149,94</td>
<td>149,07</td>
</tr>
<tr>
<td>S4-22</td>
<td>153,57</td>
<td>148,81</td>
<td>148,62</td>
<td>147,92</td>
<td>149,78</td>
</tr>
<tr>
<td>S4-23</td>
<td>153,69</td>
<td>150,97</td>
<td>151,18</td>
<td>149,73</td>
<td>148,75</td>
</tr>
<tr>
<td>Average</td>
<td>153,59</td>
<td>150,04</td>
<td></td>
<td></td>
<td>149,14</td>
</tr>
<tr>
<td>0,8 mm face sheet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S4-40</td>
<td>153,06</td>
<td>150,46</td>
<td>149,98</td>
<td>150,95</td>
<td>149,70</td>
</tr>
<tr>
<td>S4-41</td>
<td>152,49</td>
<td>149,83</td>
<td>149,77</td>
<td>151,00</td>
<td>150,60</td>
</tr>
<tr>
<td>S4-42</td>
<td>152,60</td>
<td>149,43</td>
<td>149,52</td>
<td>150,72</td>
<td>150,47</td>
</tr>
<tr>
<td>S4-43</td>
<td>152,57</td>
<td>149,95</td>
<td>149,82</td>
<td>150,58</td>
<td>150,98</td>
</tr>
<tr>
<td>S4-44</td>
<td>152,43</td>
<td>149,89</td>
<td>149,96</td>
<td>150,29</td>
<td>151,23</td>
</tr>
<tr>
<td>Average</td>
<td>152,63</td>
<td>149,86</td>
<td></td>
<td></td>
<td>150,65</td>
</tr>
</tbody>
</table>

Figure 29: Left top: Initial test configuration. Left bottom: Crushing and folding face sheet. Right: Adjusted load configuration.

To prove the importance of a proper load configuration at the top of the specimen requires two test setups:
- Initial test setup;
- Test setup with steel flanges.

Prior to the test setup with steel flanges of figure 28 the testing machine exerts a uniaxial compression force at the top at the specimen according to the initial test setup (see left side of figure 29). By performing the initial test the specimen fails due to crushing the top side of the GFRP face sheets. Therefore, the initial loading configuration with a flat steel plate on top of the specimen changes to the test setup with steel flanges. The test setup with steel flanges has a steel section on top of the specimen (see right side of figure 29). The jack force of the testing machine applies a compressive force via a ball joint into the flanges of the steel HEM 200 section (Figure 29, a). The ball joint represents a hinge connection and adjusts while the load applies onto a skew specimen. The flanges distribute the load via a thick aluminium plate into the face sheets of the specimen (Figure 29, b). The aluminium plate and a steel HEM 200 section supports the specimen at the top edge as well as the bottom edge. The flanges of the steel section enclose the specimen over a height of 25 mm along the GFRP face sheets to prevent failure at the GFRP face sheets due to lateral deformations or by exceeding the GFRP compression strength at the edges (Figure 29, c). GFRP strips fill the gap between the steel flanges and specimen.

By applying the load onto the specimen the potentiometer, positioned at 40 mm from the top of the specimen, measures very small lateral deformations of 0.1 mm at all three face sheet thicknesses. These small lateral deformations satisfy to the load introduction condition that, the GFRP face sheet almost remains straight to prevent early compression failure of the GFRP face sheet. A test is successful when failure occurs or by reaching a linear branch in the load/strain diagram to derive the compression modulus of elasticity of the GFRP face sheet. Failure in this compression test means failure of the core or face sheet material, failure of face sheets due to crushing, plastic yielding, bending or by reaching the ultimate force.

To determine the compression modulus of elasticity of the GFRP face sheet material two specimens per group contain a strain gauge to measure the axial strain. Because of the shortening of the specimen the strain of the XPS material must be equal to the strain of the GFRP face sheet material. This holds only for zero lateral deflections. The assumption of equal strains is useful to derive a relation [45] between the GFRP compression modulus of elasticity and the XPS compression material properties of section 3.5.
By applying the compression force into the specimen of figure 30 the specimen shortens over the entire cross section and results in an equal strain distribution. By assuming linear elastic material behaviour over a strain region of 0,05 to 0,5 percent the derivation of the compression modulus of elasticity leads to formula (XX).

\[
\Delta \sigma_{(xps)} = E_{xps} \frac{\Delta F}{\sum_{i=1}^{n} A_i E_i}
\]

\[
\Delta \sigma_{(xps)} = E_{xps} \frac{\Delta F}{(c L E_{xps}) + (2 t L E_{\text{face sheet}})}
\]

\[
E_{\text{face sheet}} = \frac{(\Delta F E_{xps}) - (c L E_{xps} \Delta \sigma_{(xps)})}{(2 t L \Delta \sigma_{(xps)})}
\]

\[
E_{\text{face sheet}} = \text{Compression modulus of elasticity GFRP}
\]

\[
\Delta F = \text{Compression force test S4}
\]

\[
L = \text{Length specimen test S4}
\]

\[
c = \text{Thickness core}
\]

\[
t = \text{Thickness face sheet}
\]

\[
E_{xps} = \text{Compression modulus of elasticity XPS test 3 (section 3.5) at a strain interval of 0,05 to 0,5 % .}
\]

\[
\sigma_{(xps)} = \text{Compression stress XPS test 3 (section 3.5) at a strain interval of 0,05 to 0,5 % .}
\]

First of all, Appendix E contains the test results of the individual tests and table 12 shows the average properties. Then, figure 31 shows the force-axial deformation diagram of a sandwich panel with face sheets of 0,8 mm. From the start of the test the slope of the force-axial deformation diagram slowly increases until the slope becomes linear up to failure. Specimen 40 and 42 strengthen after the first crack until local failure occurs wherefore the load decreases significantly. Due to early cracks in the these specimens, the sandwich panels with a face sheet thickness of 0,8 mm have large force variations.
Figure 31: Force-axial deformation diagram and normal distribution of a face sheet thickness of 0.8 mm. The vertical line refers to the force values for statistical processing of the average force.

The material behaviour of the GFRP face sheet is non-linear elastic (Figure 32). The local failure mechanism wrinkling occurs along the complete length of the specimen (Figure 32).

Figure 32: Left: Force-engineering strain diagram 0.8 mm face sheet. Right: Wrinkling failure.

The results of a sandwich panel with a face sheets of 1.5 mm are given in figure 33 and figure 34.
The slope of the force-axial deformation graph increases until the slope becomes linear. The specimen fails without a warning mechanism or strengthens after the first crack (specimen 21 and 22). If the wrinkling load is reached failure occurs. Wrinkling occurs along the complete length of the specimen (Figure 34). According to the average results of the force-strain diagram (Figure 34) the material behaviour of the GFRP face sheet is non-linear elastic. Despite of the coarse average line in the force-strain diagram the compression modulus of elasticity has a correlation coefficient of 0.99 and therefore equation (XX) is valid.

Figure 33: Force-axial deformation diagram and normal distribution of a face sheet thickness of 1.5 mm. The vertical line refers to the force values for statistical processing of the average force.

Figure 34: Left: Force-engineering strain diagram 1.5 mm face sheet. Right: Wrinkling failure. S4-20 face sheet plastic yield.
Then, figure 35 and figure 36 represent the average test results of the sandwich panels with a 3 mm GFRP face sheet. The first part of the slope of the force-axial deformation diagram is non-linear till a load level of 20 kN. Then, a linear or non-linear slope continues till the specimen fails by wrinkling. The wrinkling mechanisms along the complete length of the specimen (Figure 36) suddenly occurs by reaching the ultimate force. The material behaviour of the GFRP face sheet is non-linear elastic.

Figure 35: Force-axial deformation diagram and normal distribution of a face sheet thickness of 3 mm. The vertical line refers to the force values for statistical processing of the average force.

Figure 36: Left: Force-engineering strain diagram 3 mm face sheet. Right: Wrinkling failure. S4-09: face sheet plastic yield.
The statistical meaning of the normal distributions per face sheet thickness can be discussed using Table 12. The standard deviation and the kurtosis are large for a sandwich panel with face sheets of 0.8 mm. The standard deviation has a value with a magnitude of more than ten percent of the failure load. The kurtosis describes almost a flat shaped distribution. As well as the large value of the standard deviation as the kurtosis might be caused by glue agglomerations between the face sheet and the core material or small circular indentations in the face sheet surface. The agglomerations and indentations are both geometrical imperfections. The amount and magnitude of these geometrical imperfections decrease when the face sheet thicknesses increase (see also section 3.9).

Table 12: Average values cubic sandwich panel test

<table>
<thead>
<tr>
<th>Sandwich panel properties</th>
<th>Unit</th>
<th>0,8 mm</th>
<th>1,5 mm</th>
<th>3,0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure load, mean ((F_u, x))</td>
<td>[ kN ]</td>
<td>17,06</td>
<td>33,82</td>
<td>76,59</td>
</tr>
<tr>
<td>Strain at failure ((\varepsilon_u))</td>
<td>[% ]</td>
<td>0,69</td>
<td>0,79</td>
<td>1,39</td>
</tr>
<tr>
<td>Compression E-modulus GFRP</td>
<td>[ MPa ]</td>
<td>8738</td>
<td>8215</td>
<td>6295</td>
</tr>
<tr>
<td>Axial deformation at failure ((\delta_u))</td>
<td>[ mm ]</td>
<td>1,13</td>
<td>1,65</td>
<td>2,20</td>
</tr>
<tr>
<td>Standard deviation ((S_d))</td>
<td>[ kN ]</td>
<td>2,47</td>
<td>2,14</td>
<td>5,20</td>
</tr>
<tr>
<td>2,5% lower bound</td>
<td>[ kN ]</td>
<td>12,21</td>
<td>29,61</td>
<td>66,39</td>
</tr>
<tr>
<td>97,5% upper bound</td>
<td>[ kN ]</td>
<td>21,91</td>
<td>38,04</td>
<td>86,79</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>[- ]</td>
<td>-2,62</td>
<td>3,39</td>
<td>-0,14</td>
</tr>
<tr>
<td>Skewness</td>
<td>[- ]</td>
<td>-0,53</td>
<td>-1,78</td>
<td>-0,77</td>
</tr>
</tbody>
</table>

Each test on a specimen results in the failure mechanism wrinkling case I rigid base (section 2.5, failure mechanism c) independent of the varying face sheet thickness. Wrinkling occurs either next to the GFRP strips or between the strips along the complete length of the specimen (Figure 37). The XPS exceeds the tensile or compression strength perpendicular to the face sheet surface.

![Figure 37: Location failure mechanism.](image)
Only specimen S4-05 with a face sheet thickness of 3 mm (Figure 36, specimen S4-05) failed by wrinkling over the complete height of the specimen. The XPS core material of specimen S4-05 exceeds the tensile strength due to large interfacial stresses. The interfacial stresses occur between the GFRP face sheet and XPS core material. This results in a crack through the XPS core material. All other specimens locally failed on wrinkling by exceeding either the face sheet bending strength or face sheet compression strength or the core tensile strength. By exceeding the compression strength of the XPS core material (Figure 36, specimen S4-09) the face sheet compresses into the core material until wrinkling failure occurs. When the interfacial stress exceeds the tensile strength of the XPS core material (Figure 32, specimen S4-41) the face sheet rips of the core material and wrinkling failure occurs.

The proper load configuration of a test setup with steel flanges always results in the failure mechanism wrinkling. Due to the lateral support of the steel flanges at the top and bottom side of the specimen are the GFRP face sheet edges unable to fail by early crushing. Therefore, it is important to emphasize that the load configuration with steel flanges is suitable to construct the test setup of the sandwich panel buckling test of section 3.9.
3.8 CONCLUSION

The reliability of the experimental tests are given by a 95% confidence interval (CI). The experimental tests contain samples of at least five specimens. A few remarks per test are necessary to describe the most important observations per test. The two categories of the experimental tests will be discussed by:

- Material tests;
- Sandwich panel test.

The material tests consist of a GFRP face sheet test and three XPS core material test types. The orthotropic GFRP face sheet has a woven fabric with similar material properties into two fibre directions. The statistical analysis proves the constancy of a well-engineered material with a small variation. The material behaviour of the GFRP face sheets loaded in tension is linear elastic to face sheets of 0,8 mm and 1,5 mm and nonlinear elastic to 3,0 mm thickness. The face sheets elongate until failure suddenly occurs. The tensile properties of the GFRP face sheets are evaluated in table 13. The poison ratio can only be used as indication value (see section 3.3).

Table 13: Tensile engineering material properties per GFRP face sheet thickness

<table>
<thead>
<tr>
<th>GFRP tensile properties</th>
<th>Unit</th>
<th>0,8 mm</th>
<th>1,5 mm</th>
<th>3,0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength, mean ((\sigma_u, x))</td>
<td>[ MPa ]</td>
<td>134</td>
<td>80</td>
<td>55</td>
</tr>
<tr>
<td>Tensile strain at failure ((\varepsilon_u))</td>
<td>[%]</td>
<td>1,646</td>
<td>1,280</td>
<td>0,996</td>
</tr>
<tr>
<td>Tensile modulus of elasticity ((E))</td>
<td>[ MPa ]</td>
<td>9924</td>
<td>7218</td>
<td>6679</td>
</tr>
<tr>
<td>Poison ratio</td>
<td>[-]</td>
<td>0,37</td>
<td>0,10</td>
<td>0,27</td>
</tr>
</tbody>
</table>

The XPS material properties (Table 14) are defined by a shear test, tensile test and compressive test. A shear test on the XPS core material conform the ISO Standard 1922 [42] results in the shear strength and shear modulus of elasticity. To prevent bending of the specimen the test setup of the test Standard has changed by adding two roller supports to support the specimen in lateral direction. The material behaviour of the force deformation diagram is non-linear. At the corners of the XPS shear peak stresses occur. These peak stresses develop shear cracks along the complete length of the XPS specimen until the XPS fails. A very small standard deviation supports the reliability of the test results. The material properties of the XPS core material measured in compression and tension of the experimental tests are the same as the values given by the manufacturing company. The material behaviour of the XPS loaded in compression is non-linear elastic. The material behaviour of the XPS loaded in tension is also non-linear elastic, but has a longer linear elastic branch at the lower stress levels.

Table 14: XPS engineering properties

<table>
<thead>
<tr>
<th>XPS properties</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear strength, mean ((\tau_v, x))</td>
<td>0,489 [ MPa ]</td>
</tr>
<tr>
<td>Shear modulus of elasticity ((G))</td>
<td>10,4 [ MPa ]</td>
</tr>
<tr>
<td>Compression strength, mean ((\sigma_w, x))</td>
<td>0,404 [ MPa ]</td>
</tr>
<tr>
<td>Compression strain at failure ((\varepsilon_u))</td>
<td>2,287 [%]</td>
</tr>
<tr>
<td>Initial compression modulus of elasticity ((E))</td>
<td>30,3 [ MPa ]</td>
</tr>
<tr>
<td>Tensile strength, mean ((\sigma_u, x))</td>
<td>0,715 [ MPa ]</td>
</tr>
<tr>
<td>Tensile strain at failure ((\varepsilon_u))</td>
<td>4,572 [%]</td>
</tr>
<tr>
<td>Initial tensile modulus of elasticity ((E))</td>
<td>33,9 [ MPa ]</td>
</tr>
</tbody>
</table>

The load configuration test showed that a small adjustment of the test configuration changes the failure mechanism from GFRP face sheet compression failure to wrinkling failure. All specimens failed due to wrinkling can be categorised to wrinkling case I rigid base of section 2.5 failure mechanism c, according to the literature. At the
occurrence of wrinkling failure the face sheet bends and fails or the face sheet deforms until a plastic hinge develops and finally fails. Table 15 evaluates the results of the load configuration test.

Table 15: Sandwich panel properties

<table>
<thead>
<tr>
<th>Sandwich panel properties</th>
<th>Unit</th>
<th>0,8 mm</th>
<th>1,5 mm</th>
<th>3,0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure load, mean ($F_u, \bar{x}$)</td>
<td>[ kN ]</td>
<td>17,06</td>
<td>33,82</td>
<td>76,59</td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>[ % ]</td>
<td>0,69</td>
<td>0,79</td>
<td>1,39</td>
</tr>
<tr>
<td>GFRP compression modulus of elasticity ($E$)</td>
<td>[ MPa ]</td>
<td>8738</td>
<td>8215</td>
<td>6295</td>
</tr>
<tr>
<td>Axial deformation at failure ($\delta_u$)</td>
<td>[ mm ]</td>
<td>1,13</td>
<td>1,65</td>
<td>2,20</td>
</tr>
</tbody>
</table>
3.9 TEST TYPE 6: INSTABILITY OF THE SANDWICH WALL PANEL

To investigate the instability behaviour of a GFRP sandwich wall panel experimental tests were carried out. A testing machine is used to apply a uniaxial in-plane compressive force until the test specimen fails. The test is deformation controlled. (Figure 38). Two adjacent positioned actuators apply the compressive force at the lower end of the sandwich panel. Two load cells at the upper part of the test setup measure the applied force. To understand the importance of the test results three parts of the test setup will be explained:

- Test frame;
- Measure equipment;
- Geometry of the specimen.

![Test setup and technical drawing](image)

Figure 38: Left: Test setup ‘back side’ with additional frame and part 1 and 2. Right: Technical drawing with numbers referring to the measure equipment.

3.9.1 Test frame

The test frame is a closed stand-alone frame around the sandwich panel specimen. During the test deformations of the test frame are assumed to be negligible. A uniform distributed load is achieved by using two hydraulic actuators in parallel action. To prevent lateral instability of the actuators these have been located at the lower end of the test frame. Two load cells are located at the opposite end of the test frame. Either lower end and upper end support of the panel consist of rollers (hinges) which are located within the two white dashed areas indicated with number one.
and number two (Figure 1). In what now follows is, a detailed description of the both roller supports will be given according to the conditions investigated in section 3.7.

The lower steel section (HEB 300) of the test frame supports two actuators. A steel section (HEB 150) next to the actuator operates as restraining lateral support to the non-movable part of the actuator (Figure 39). The movable part of the actuator can freely move in vertical direction (y-direction) and contains a round steel rod on top of the actuator. The round steel rod carries the web of the steel HEM 200 section (Figure 39 right side). Two thin Teflon layers are added between the steel round rod and the HEM section to prevent any resistance between the movable steel parts. Within the flanges of the HEM section, M12 bolts prevent lateral displacements of the HEM section but allow the HEM section to rotate freely around the round steel rod. The HEM section is the same HEM section of test 5 (Section 3.7). The load conditions as discussed in the ‘test setup with steel flanges’ of section 3.7 are used. The actuator (Figure 39) introduces a force on the round steel rod via the HEM section into the sandwich panel (see figure 29 for the load distribution through the HEM section).

Both hinged supports at lower and upper end are hinged in the same way but at the upper end the displacements of the round steel rod is restrained only allowing rotation. \((u_x = u_y = u_z = 0)\).

### 3.9.2 Measure equipment

The two hydraulic actuators attached to the lower part of the test frame are both able to introduce a maximum force of 500 kN. A flow panel is used (Figure 40) to perform a deformation controlled test. At the start of the test the actuator introduces a pre-load of 10 percent of the ultimate load on the specimen to remove clearance in the test frame. The test speed depends on the face sheet thickness of the sandwich panel. By reaching any type of failure the test is terminated. At the upper part of the test frame two load cells take the applied force. The load cells are in line with the actuators. A load cell of 150 kN and 350 kN with an accuracy of 20 N and 35N are used to measure the applied force of sandwich panels with a face sheet thickness of 0.8 mm and 1.5 mm and with a face sheet thickness of 3 mm, respectively.
An additional steel frame containing 6 potentiometers is used to observe the out-of-plane deformations at mid height of the sandwich panel (see location potentiometers in Appendix F). The additional frame is not attached in any way to the test frame to exclude possible deformations of the test frame from the sandwich panel deformation. A thin copper wire is used to bring the lateral deformations of the sandwich panel face sheet (Figure 41) to the potentiometers. The potentiometers have a measuring range of 750 and 940 millimetres and an accuracy of 0.02 mm. At the start of the test the copper wire is perpendicular to the sandwich panel. During the test the sandwich panel shortens and changes one end of the copper wire attachment. However, the effect of the changing angle is negligible small compared to the measured out-of-plane deformations. Two potentiometers (AE sensor WS10-250) measure the in-plane (axial) shortening of the sandwich panel from HEM 200 section to HEM 200 section. The deformations of the HEM 200 section itself are negligible small compared to the deformations of the sandwich panel. The calculation of the test frame deformations are excluded. The potentiometer to measure the in-plane (axial) shortening has a measuring range of 250 millimetres and an accuracy of 0.015 mm. The hinge and roller support allow the HEM 200 section to rotate. Two liquid based inclinometers measure the inclination angle of the upper and lower HEM 200 section (Figure 41). The inclinometer (Seika) has a range from minus 45 to 45 degrees and an accuracy of 0.001 degrees.

Four wire strain gauges (PL-90-11) measure the in-plane (axial) strain of the sandwich panel face sheet at mid height. The strain gauge at the surface of the face sheet measure the axial strain over the vertical line between the actuator...
and the load cell. The strain gauges have a length of 90 mm and a strain limit of two percent. The location of the measure equipment is given in figure 42 and Appendix F. The name of the specimen (S6__) distinguishes the front side of the specimen from the back side of the specimen.

Figure 42: Measure equipment with 100-101 are load cells, 102-107 are potentiometers to measure out-of-plane deformations, 109-110 are potentiometers to measure the in-plane (axial) shortening, 110-111 are inclinometers to measure the rotation and 700-703 are strain gauges.

3.9.3 Geometry and visual check

A visual examination of the quality of the sandwich panels has been performed. The constituent materials of the sandwich panel, i.e. GFRP, adhesive and XPS, indicate imperfections in the sandwich panel geometry. The geometrical imperfections of the sandwich panel are (Figure 43):

- Gaps between the XPS plates (type A);
- Coarseness of the GFRP face sheet surface (type B);
- Adhesive agglomeration (type C).

A disadvantage in the manufacturing process of XPS plates is the missing adhesive at the side edges. Gaps between XPS plates (type A) occur in all specimens and vary from one to three millimetres. Gaps between the XPS plates create an extra disadvantage for sandwich panels with thin face sheets of 0,8 mm. These thin face sheets are more sensitive to wrinkling than thicker face sheets at gaps. Sandwich panels with a face sheet thickness of 0,8 mm have a coarse face sheet surface. Small circular indentations of approximate one millimetres are visible in the face sheet material and extends over the complete sandwich panel surface. These indentations only occur at sandwich panels with thin face sheets likely caused during the manufacturing process or transport (type B). A combination of a gap
between XPS plates and an indentation in the face sheet material may initiate premature failure of the sandwich panel.

Figure 43: Left type A, middle type B and right type C.

In the manufacturing process a vacuum-assisted resin transfer moulding (VARTM) technique is used to produce sandwich panels. Slots in the XPS surface allow redundant resin to escape out of the sandwich panel. At the edges of the sandwich panel the adhesive can agglomerate at the end of the slot between the face sheet material and XPS. Because of local adhesive agglomerations the sandwich panel thickness might vary (type C). Table 16 contains the geometrical imperfections of type A, B and C per specimen.

Table 16: Geometrical imperfections

<table>
<thead>
<tr>
<th>Specimen</th>
<th>S6-00 (3 mm)</th>
<th>S6-01 (3 mm)</th>
<th>S6-02 (3 mm)</th>
<th>S6-03 (1,5 mm)</th>
<th>S6-04 (0,8 mm)</th>
<th>S6-05 (0,8 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A – gaps XPS</td>
<td>≤ 3 mm</td>
<td>≤ 3 mm</td>
<td>≤ 1 mm</td>
<td>≤ 2 mm</td>
<td>≤ 1 mm</td>
<td>≤ 2 mm</td>
</tr>
<tr>
<td>Type B – Indentations</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Front and back</td>
<td>Front and back</td>
</tr>
<tr>
<td>Type C – glue agglomeration</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>≤ 1 mm</td>
<td>≤ 2 mm</td>
</tr>
</tbody>
</table>

The face sheet thickness of a sandwich panel categorise the specimens into three groups by 0,8 mm, 1,5 mm and 3 mm. Table 17 represents per group the dimensions, i.e. the thickness, length and width, of the five specimens. The rectangular specimens each have a fixed width and height of 900 and 2650 mm. The XPS of the sandwich panel has a constant thickness of 150 mm at each group.
Table 17: Geometry test specimens. Dimensions are in millimetres.

<table>
<thead>
<tr>
<th>Name:</th>
<th>S6-00*</th>
<th>S6-01*</th>
<th>S6-02</th>
<th>S6-03</th>
<th>S6-04</th>
<th>S6-05</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
<td>3,0</td>
<td>3,0</td>
<td>3,0</td>
<td>1,5</td>
<td>0,8</td>
<td>0,8</td>
</tr>
<tr>
<td>d1</td>
<td>156</td>
<td>156</td>
<td>156</td>
<td>154</td>
<td>151</td>
<td>152</td>
</tr>
<tr>
<td>d2</td>
<td>156</td>
<td>156</td>
<td>156</td>
<td>154</td>
<td>151</td>
<td>153</td>
</tr>
<tr>
<td>d3</td>
<td>157</td>
<td>157</td>
<td>156</td>
<td>154</td>
<td>151</td>
<td>153</td>
</tr>
<tr>
<td>d4</td>
<td>156</td>
<td>156</td>
<td>156</td>
<td>154</td>
<td>151</td>
<td>151</td>
</tr>
<tr>
<td>Average</td>
<td>156,3</td>
<td>156,3</td>
<td>156,0</td>
<td>154,0</td>
<td>151,0</td>
<td>152,3</td>
</tr>
<tr>
<td>b1</td>
<td>901</td>
<td>901</td>
<td>900</td>
<td>899</td>
<td>901</td>
<td>901</td>
</tr>
<tr>
<td>b2</td>
<td>900</td>
<td>900</td>
<td>899</td>
<td>898</td>
<td>901</td>
<td>900</td>
</tr>
<tr>
<td>b3</td>
<td>898</td>
<td>898</td>
<td>901</td>
<td>899</td>
<td>898</td>
<td>904</td>
</tr>
<tr>
<td>b4</td>
<td>899</td>
<td>899</td>
<td>900</td>
<td>898</td>
<td>899</td>
<td>900</td>
</tr>
<tr>
<td>Average</td>
<td>899,5</td>
<td>899,5</td>
<td>900,0</td>
<td>898,5</td>
<td>899,8</td>
<td>901,3</td>
</tr>
<tr>
<td>h1</td>
<td>2330</td>
<td>2638</td>
<td>2648</td>
<td>2650</td>
<td>2650</td>
<td>2653</td>
</tr>
<tr>
<td>h2</td>
<td>2332</td>
<td>2639</td>
<td>2646</td>
<td>2650</td>
<td>2650</td>
<td>2653</td>
</tr>
<tr>
<td>h3</td>
<td>2331</td>
<td>2639</td>
<td>2648</td>
<td>2650</td>
<td>2650</td>
<td>2651</td>
</tr>
<tr>
<td>h4</td>
<td>2331</td>
<td>2639</td>
<td>2647</td>
<td>2650</td>
<td>2650</td>
<td>2650</td>
</tr>
<tr>
<td>Average</td>
<td>2331,0</td>
<td>2638,8</td>
<td>2647,3</td>
<td>2650,0</td>
<td>2650,0</td>
<td>2651,8</td>
</tr>
</tbody>
</table>

Hatched area = Front side specimen
* = The length of specimen S6-00 and S6-01 are cut.
3.9.4 Specimen S6-00 and S6-01

At the upper part of specimen S6-01 between the 3 mm face sheet and core material over an area of 100x900 mm² (height x width) the adhesive misses because of a shortcoming in the manufacturing process as mentioned above. Premature failure of specimen S6-01 occurs at an axial load of 94,6 kN (Figure 44). A deformation is applied by 2 mm/min and results in the linear behaviour of the force-in-plane axial shortening diagram (Figure 44). The specimen material behaviour is linear elastic (Figure 44 right diagram). Figure 45 shows by the ‘111 hinge support’ a rotation of zero up to a force of 50 kN. After a force of 50 kN the face sheet of the specimen starts to wrinkle and the hinge support rotates (upper part specimen). The out-of-plane deformations during the test remain zero.

Figure 44: Left: Force-average axial shortening diagram. Right: Stress-engineering strain diagram.

Figure 45: Left Force-rotation diagram and right failure caused by the missing adhesive between face sheet and core (S6-01).
Without the top section of specimen S6-01 with a height of 300 mm the remaining specimen part is usable to perform a new instability test. As such the new specimen, named S6-00, has a new geometry of 156x900x2330mm (thickness x width x height). The face sheet has a thickness of three millimetres. Specimen S6-00 is the shortest specimen and as can be expected the specimen with the highest in-plane load bearing resistance. S6-00 was the last specimen of the buckling test series and in contrary to the other specimens S6-00 has a perfect square geometry. The actuator applies a load to obtain a deformation of 3 mm/min. A summation of the applied force measured by two load cells represent the maximum force in the specimen with a linear relation to the average in-plane (axial) shortening (Figure 46 left diagram). The right diagram of figure 46 shows small out-of-plane deformations at the front and back side of the specimen. The diagram of the force to the out-of-plane deformation has a non-linear behaviour due to a changing derivative and indicates global buckling of the specimen. The deformations at different points over the width of the specimen differ by 1 mm either at the front side or at the back side of the specimen. The small deformations exclude twisting around the y-axis of the specimen (Figure 42, coordinate system). The out-of-plane deformations result in bending.

Figure 46: Left: Force-average axial shortening diagram. Right: Force-out-of-plane deformations diagram with 102, 103 and 104 are measured at the back side of the panel and 105, 106 and 107 are measured at the front side of the panel.

Figure 47 shows that the rotations of the supports confirm that the specimen bends. From zero to 50 kN a very small rotation occurs. The roller support at the lower end of the specimen rotates more than the hinge support at the upper part of the specimen. Up to 150 kN describes the force-strain diagram a linear elastic relation (Figure 47 right diagram). Prior to failure the strain at the back side of the specimen is higher than at the front side of the specimen. The strain deviation describes a combination of bending and normal stresses acting in the specimen.
Local buckling or wrinkling (delamination) failure at both face sheets at the upper part of the specimen occurs without warning and within a split second. The 50 frames per second of the video tape are unusable to identify the first crack at failure at the upper part of the specimen. Prior to failure has the specimen a single curvature according to the stress-rotation diagram (Figure 47 left diagram) and after failure has the specimen a double curvature according to figure 48. Appendix G contains more photos of the wrinkling failure.

Figure 47: Left: Force-rotation diagram. Right: Force-engineering strain diagram.

Figure 48: Wrinkling failure front side specimen with at the left curvature R1 and R2 and right XPS fails by exceeding the tensile strength.
3.9.5 Specimen S6-02

The actuators apply a load to obtain a deformation of 1.5 mm/min. Figure 49 represents a linear behaviour. Up to 120 kN the specimen with face sheets of 3 mm remains straight without any out-of-plane deformations (Figure 49 right diagram). When the load increases the out-of-plane deformations increase as well as the bending stresses in the specimen. These deformations are of the same magnitude at both sides of the specimen which excludes twisting. The force-out-of-plane deformation diagram has a non-linear behaviour and indicates global buckling. From the test was observed that the specimen buckled at failure. The out-of-plane deformation reaches a maximum of 7.69 mm.

Figure 49: Left: Force-average axial shortening diagram. Right: Force-out-of-plane deformations diagram with 102, 103 and 104 are measured at the back side of the panel and 105, 106 and 107 are measured at the front side of the panel.

Figure 50: Left: Force-rotation diagram. Right: Force-engineering strain diagram.
At the start of the test, the supports rotate until the structure reaches a new equilibrium (Figure 50 left diagram). The roller support at the bottom of the specimen increases more than the hinge support at the upper part of the specimen. Meanwhile increasing the compression strain at the front and back side of the specimen (Figure 50 right diagram). Because of bending decreases the strain at the less compressed side of the specimen and increases the strain at the more compressed side of the specimen. The force-strain diagram has a linear elastic behaviour until a force of 200 kN. By reaching the failure load, brittle failure of the specimen causes failure modes at six different locations spread over the front and back side of the specimen. The failure modes are Euler/shear buckling, wrinkling, compressive failure face sheet and core shear failure, see Appendix G and figure 51.

Figure 51: Left: Wrinkling failure (front side specimen). Middle: 1.) Core shear failure, 2.) Type A gap and 3.) Wrinkling failure (back side specimen). Right: Compressive failure face sheet (back side specimen).
### 3.9.6 Specimen S6-03

The actuator applies a load to obtain a deformation of 1,5 mm/min. The force to the average in-plane (axial) shortening has a linear response of the panel with face sheets of 1,5 mm (Figure 52 left diagram). The equal out-of-plane deformations at both sides of the specimen (Figure 52 right diagram) show that the thickness of the specimen remains equal to the initial thickness of the specimen and no twisting of the specimen occurs. The force to out-of-plane deformation diagram has a non-linear behaviour that indicates global buckling. By an increasing out-of-plane deformation increases the curvature of the specimen and therefore the rotation of the hinge supports.

![Graph showing linear response of in-plane shortening](image1)

![Graph showing non-linear out-of-plane deformation](image2)

**Figure S2:** Left: Force-average axial shortening diagram. Right: Force-out-of-plane deformations diagram with 102, 103 and 104 are measured at the back side of the panel and 105, 106 and 107 are measured at the front side of the panel.

![Graph showing force-rotation and force-engineering strain](image3)

**Figure S3:** Left: Force-rotation diagram. Right: Force-engineering strain diagram.
Figure 53 (left diagram) represents the stress-rotation diagram of the specimen S6-03. While the stress on the specimen increases the rotation of the hinge supports increase till the specimen reach a new state of equilibrium. The rotation measured by the inclinometer has a coarse slope because of the accurateness of the inclinometer and the friction of the support during rotation. The roller support at the bottom of the specimen rotates more than the hinge support at the upper part of the specimen. This is obvious compared to the location of failure of the specimen. The rotation at the lower end and upper end of the specimen causes a bending moment in the specimen. The bending moment increases the compressive strain at the compressed face sheet and decreases the compressive strain at the opposite face sheet. Figure 53 (right diagram) indicates this strain deviation by an increasing and decreasing strain. As long as the specimen is only subjected to compression the GFRP face sheet has a linear elastic material behaviour. By an increasing bending moment the material behaviour of the GFRP face sheet becomes non-linear elastic.

The additional compression force caused by the bending moment increases the pressure at the compressed GFRP face sheet at the front side of the specimen. The compression force at the front side of the specimen is larger than at the back side of the specimen. The higher compressive force results in sudden failure of the GFRP face sheet at the front side of the specimen (Figure 54). The XPS core material attached to the GFRP face sheet and the shape of the failure mechanism indicates wrinkling. By exceeding the wrinkling stress exceeds the XPS core material the tensile strength perpendicular to the face sheet and rips the GFRP face sheet of the XPS core material.

Figure 54: Left: Wrinkling occurs at the front side of the specimen. Middle: Failure at location 1. Right: The core material has failed and sticks at the face sheet at location 2.
3.9.7 Specimen S6-04

To obtain a deformation of 1,0 mm/min the actuators apply a compression load to the specimen. Figure 55 shows the linear relation between the force and average in-plane (axial) shortening of the specimen with a face sheet thickness of 0,8 mm. The force-axial deformation diagram has two distortions at the start of the test. Firstly, the pre-load cycle. And secondly, an interruption in the test data because of a malfunctioning load cell.

![Graphs showing force-average axial shortening and force-out-of-plane deformations](image)

Figure 55: Left: Force-average axial shortening diagram. Right: Force-out-of-plane deformations diagram with 102, 103 and 104 are measured at the back side of the panel and 105, 106 and 107 are measured at the front side of the panel.

The pre-load cycle at the start of the test can be recognised in the force-out-of-plane deformation diagram (Figure 55 right diagram). The pre-load cycle causes a plastic out-of-plane deformation. The force-out-of-plane deformation diagram has a non-linear behaviour. The average out-of-plane deformation at failure is 1,88 mm. The small deformations of 1,88 millimetres are too small to perform an accurate measurement with a potentiometer as can be seen at the rough lines of the diagram. The small out-of-plane deformations indicate that the specimen remains almost straight. Due to the relative small bending deformations of the sandwich panel the normal stress dominates above the bending stress.
The small out-of-plane deformations of the specimen correspond to the rotation of the supports (Figure 56 left diagram). By loading the specimen both supports rotate till they reach a new state of equilibrium. Due to a geometrical imperfection at the upper edge of the specimen the hinge support rotates more than the roller support at the lower edge of the panel. During the test the rotation of the upper hinge support of the panel remains constant while the rotation of the lower roller support increases. The stress-strain diagram of the sandwich panel represents linear elastic material behaviour (Figure 56 right diagram).

In the upper right corner (figure 57 left photo) of the front side of the specimen occurs a small wrinkle. Prior to the ultimate load at the upper left corner (Figure 57) a second wrinkle initiates. These wrinkles are located at the same horizontal line at the front side of the specimen. By reaching the ultimate load the specimen fails by wrinkling. The wrinkle at the left corner develops over the complete width of the specimen as can be seen in figure 57 with a time interval of 0,04 seconds between the first and second photo. While wrinkling occurs the core material exceeds the tensile strength perpendicular to the face sheet material and the face sheet material locally delaminates (Appendix G).

Figure 56: Left: Force-rotation diagram. Right: Force-engineering strain diagram.

Figure 57: Left: Wrinkle at upper right corner. Photo’s middle: Two frames of the video with a time interval of 0,04 seconds. Right: Wrinkling failure with a local delamination of the face sheet material.
3.9.8 Specimen S6-05

The pre-load of ten percent of the ultimate load on the specimen removes clearance in the test frame. The actuator applies a load to obtain a deformation of 1.0 mm/min. Figure 58 represents the linear behaviour between the load and average in-plane (axial) shortening. At 53 kN the average in-plane axial shortening increases and the out-of-plane deformations start to accelerate (Figure 58 right diagram) due to local buckling. At the first wrinkle the out-of-plane deformation has a value of two millimetres. At a load level of 53 kN the force-out-of-plane deformation behaviour is non-linear and linear after the load level of 53 kN.

![Figure 58: Left: Force-average axial shortening diagram. Right: Force-out-of-plane deformations diagram with 102, 103 and 104 are measured at the back side of the panel and 105, 106 and 107 are measured at the front side of the panel.](image)

![Figure 59: Left: Force-rotation diagram with a photo of the wrinkles at a load of 53 kN. Right: Stress-engineering strain diagram.](image)
Local buckling is identifiable from small wrinkles (Figure 59 left diagram) along the longitudinal edge at the front side of the specimen. Meanwhile, the specimen bends and the rotation of the roller support at the lower part of the specimen increases. The hinge support remains constant for a while and finally increase to a rotation of 0.0017 radians. The stress-strain diagram (Figure 59 right diagram) shows at the same load level of 53 kN an increasing strain at the front side of the specimen. Up to 33 MPa the stress-strain relation remains linear elastic and mechanics according to the theory of elasticity is valid to evaluate stresses in the cross-section. Beyond the 33 MPa the stress-strain relation is non-linear elastic.

By reaching the ultimate compression load brittle failure occurs. It is clear from the small wrinkles along the longitudinal edge of the specimen that local buckling initiated to the failure mechanism wrinkling. Figure 60 shows the growing crack by a time interval of 0.04 seconds. The upper wrinkle of photo 1 of the same figure increases faster due to a geometrical imperfection of type A gaps between the XPS plates of subsection 3.9.3, see also Appendix G. At the critical compression load the wrinkle develops over the complete width of the specimen.

Figure 60: Local buckling along the longitudinal edge of the front side of the specimen in photo 1 and 2 initiates the buckling mode wrinkling of photo 3. Because of the zoomed view the quality of the photos obtained from the video camera are low.
3.9.9 Discussion

This section discusses the topics about the results of sandwich panel buckling test and the compression modulus of elasticity derived from three experimental tests (test 1, 5 and 6).

In general, from the force-out-of-plane diagram (Figure 61) it is clear that at bifurcation the out-of-plane deformations increase. The deformed sandwich panel may be influenced by initial imperfections. The increasing load on the specimen and the increasing out-of-plane deformations result in a second order effect. This type of geometrical nonlinearity causes an additional internal bending moment in the specimen. The internal bending moment increases the normal stress in the compressed face sheet. The compressed face sheet becomes more sensitive to face sheet wrinkling. The latter, face sheet wrinkling occurs to all specimens. The second order effect influences the face sheet wrinkling (local) mode.

While the compression stress in the face sheet increase small wrinkles develop along the complete length of the face sheet or the sandwich panel fails due to a chain reaction of several failure mechanisms at the same moment. These mechanisms can be face sheet wrinkling, core shear failure, compressive failure face sheet, local delamination face sheet or local adhesive failure (Table 18). At the occurrence of either a small face sheet wrinkle or the overall increasing out-of-plane deformations the local stiffness response of the compressed face sheet decrease. The core material provides the lateral support of the face sheet. Due to face sheet wrinkling the face sheet bends and results in local failure of the core material. The core material exceeds the compressive or tensile stresses perpendicular to the face sheet. Whether the face sheet wrinkle presses into the core material (inside direction) or rips the face sheet of the core material (outside direction) is arbitrary despite of the core material properties with an ultimate compression stress of 57% of the ultimate tensile stress.

Figure 61: Force-Out-of-plane deformation diagram with failure mechanisms. S6-00: L = 2650 mm. S6-01 to S6-05: L = 2330 mm.
Table 18: The order of the failure mechanisms is given by a sequence number.
* = Small wrinkles occur along complete face sheet edge length.

<table>
<thead>
<tr>
<th>Specimen (face sheet thickness)</th>
<th>S6-00 (3 mm)</th>
<th>S6-01 (3 mm)</th>
<th>S6-02 (3 mm)</th>
<th>S6-03 (1,5 mm)</th>
<th>S6-04 (0,8 mm)</th>
<th>S6-05 (0,8 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.) 2nd order imperfection included</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b1.) Face sheet wrinkling</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1*</td>
<td></td>
</tr>
<tr>
<td>b2.) Face sheet wrinkling at gap</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c.) Core shear failure</td>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d.) Compressive failure face sheet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>e.) Local delamination face sheet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>f.) Local adhesive failure</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The sandwich panel failure behaviour is discussed per face sheet thickness.

The second order effect initiated failure to specimens with a face sheet of 3,0 mm. Due to a shorter buckling length of specimen S6-00 fails specimen S6-00 with the same face sheet thickness at a higher buckling load than specimen S6-02. Sandwich panels with face sheets of 3,0 mm thickness reach bifurcation at higher loads than thinner face sheets. The failure mechanism of both specimens S6-00 and S6-02 (3,0 mm) were initiated by a geometrical imperfection, namely the presence of a gap in the core material (Figure 62). Face sheet wrinkling occurred to both face sheets at both sides of the sandwich panel. The wrinkle of the face sheet over the gap was ripped of the core material.

The out-of-plane deformations of a specimen with 1,5 mm face sheets are larger compared to the specimens with a face sheet thicknesses of 3,0 or 0,8 mm. These deformations occur either due to a lower sandwich panel stiffness or due to initial imperfections. According to figure 62 local initial imperfections in the face sheet surface and a significant amount of gaps in the core material were not observed. Imperfections can most likely be assigned to the Euler (global) buckling mode. From the start of the test (Figure 61) the specimen bends without any sign of wrinkles along the face sheet edge in contrary to specimens with a face sheet thickness of 0,8 mm discussed later on. The out-of-plane deformations of specimen S6-03 increase and show similar interaction buckling behaviour like the sandwich panels with face sheets of 3,0 mm thickness. At failure sandwich panel face sheet wrinkling in a single face sheet occurs. The face sheet wrinkling causes a sudden stiffness loss of the complete structure wherefore failure occurs.
From sandwich panels (S6-04 and S6-05) with 0.8 mm face sheets, it might be obvious from the diagram (Figure 61) that the increasing out-of-plane deformations assign the second order effect to the failure mechanism that initiated face sheet wrinkling. However, test results of S6-04 and S6-05 confirm that face sheet wrinkling behaviour occurred rather than buckling due to the second order effect. The rotations of the supports of specimen S6-04 were almost zero while the axial shortening increased to approximate 15 mm. The same tendency is found to specimen S6-05. Up to 75% of the ultimate force, the rotations of the supports remained almost zero while the axial shortening increased to approximate 8 mm. Face sheet wrinkles developed along the edges of the sandwich panel. From the initial circular indentations and initial glue agglomerations on the specimen it is more likely that these local geometrical imperfections (Figure 62) initiated face sheet wrinkling failure [14]. Local geometrical imperfections are observed in the order of the face sheet thickness (0.8 mm).

Initial local geometrical imperfections develop face sheet wrinkling in a single face sheet and enforce the sandwich panel to bend. This single face sheet wrinkling behaviour is responsible for a significant stiffness loss in the complete sandwich panel resulting in failure (Figure 57 and figure 60). The presence of gaps in the core material results to an additional stiffness loss to the global sandwich panel stiffness and to the local face sheet bending stiffness.

Finally, measurements of the face sheet compression modulus of elasticity are achieved to the face sheets of sandwich panel configurations of test 5 and test 6. From the stress-strain diagrams it is assumed that only the face sheets take the normal stresses into account without any contribution of the core material. From this assumption the average face sheet compression modulus of elasticity is given per test and face sheet thickness (Table 19). According to the literature [28] and the results from the experimental tests the face sheet compression modulus of elasticity is assumed to be equal to the face sheet tensile modulus of elasticity.

Table 19: GFRP face sheet compression modulus of elasticity per face sheet thickness.

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>0.8 mm</th>
<th>1.5 mm</th>
<th>3.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1: Tensile modulus of elasticity</td>
<td>[ MPa ]</td>
<td>9924</td>
<td>7218</td>
<td>6679</td>
</tr>
<tr>
<td>Test 5: Compression modulus of elasticity</td>
<td>[ MPa ]</td>
<td>8738</td>
<td>8215</td>
<td>6295</td>
</tr>
<tr>
<td>Test 6: Compression modulus of elasticity</td>
<td>[ MPa ]</td>
<td>9647</td>
<td>7299</td>
<td>7031</td>
</tr>
<tr>
<td>Compression modulus of elasticity</td>
<td>[ MPa ]</td>
<td>9924</td>
<td>7218</td>
<td>6679</td>
</tr>
</tbody>
</table>

Figure 62: Geometrical imperfections and failure location. 1 = Gap between XPS plates, 2 = Line between two adjacent XPS plates, Red cross and red dashed line = location of failure. Specimen S6-00, S6-02 and S6-03 represent the gaps by the left and right edge. Specimen S6-04 and S6-05 represent the left edge, front side, right edge and back side.
3.9.10 Conclusion

In general, conclusions of the performed instability sandwich wall panel tests are:

− Rotations of the supports remain (almost) equal but the axial shortening of the sandwich panel increase. This behaviour refers to the geometric instability type wrinkling and occurs to sandwich panels with 0,8 mm face sheets.
− Wrinkles occur along the sandwich panel edge to face sheet thicknesses of 0,8 mm.
− Thin face sheets of 0,8 mm are more sensitive to failure due to local imperfections than thick face sheets.
− Local initial imperfections in a 0,8 mm face sheet are in the order of the face sheet thickness.
− Due to the second order effect the out-of-plane deformations increase and a localization of compression stresses result in face sheet wrinkling case I rigid base. As a result interaction buckling the geometric instability type wrinkling causes failure in the core and/or face sheet material.
− Interaction buckling occurs to sandwich panels with face sheets of 1,5 and 3,0 mm.
− Interaction buckling results in a significant global stiffness loss wherefore failure occurs.
− Out-of-plane deformations develop from initial imperfections of the Euler (global) buckling mode.
− The sandwich panel fails at a combination of the following types: Face sheet compressive failure, local delamination face sheet, core material tensile failure and core shear failure.
− The GFRP face sheet compression modulus of elasticity is assumed to be equal in compression and tension.
4. **NUMERICAL STUDY**

The experimental research contains four material property test types and two sandwich panel test types. The latter two test types will be simulated by two numerical models according to the finite element method (FEM) using in the program Abaqus/CAE 6.12 [46]. The experimental test on the cubic (short) sandwich panel (section 3.7) is performed to examine the load introduction conditions at the top edge of the sandwich panel and to give an indication of the compression properties of the GFRP face sheet. Only the axial stiffness response of a cubic sandwich panel loaded in compression will be simulated in the first numerical model using a geometric non-linear (GNL) analysis and validated by the results of the experimental tests. The second GNL analysis simulates the instability behaviour of the sandwich wall panels (section 3.9).

Numerical modelling is used to describe the buckling behaviour of sandwich panels by global and local geometrical imperfections. The variable parameters length, face sheet thickness, imperfections, and load conditions will be considered. The numerical model is used to validate or approximate the buckling behaviour observed in the experimental tests.

![Geometry sandwich panels](image)

Figure 63: Geometry sandwich panels

An extended explanation of these two numerical models (Figure 63) will be given by the sections:

- Pre-processing, section 4.1
- Solving, section 4.2
- Model validation short sandwich panels ($L = 150$ mm), section 4.4
- Model validation large sandwich panels ($L = 2650$ mm), section 4.5

The pre-processing section threatens the input data of the numerical model. The solving section gives a brief description of the analysis and solution method. Then, two sections treat the numerical models to validate the results of the experimental tests.
4.1 PRE-PROCESSING

The required input data to perform a finite element (FE) analysis will be discussed in this pre-processing section. The simulation of out-of-plane buckling behaviour of a sandwich panel loaded in compression can be performed using a two dimensional (2D) in-plane model. This model is able to simulate buckling behaviour with an arbitrary thickness. More assumptions are:

- Support conditions are limited by the conditions of an eigenvalue analysis.
- Isotropic face sheet and core material behaviour.
- The face sheet centre line is constrained to the core without any offset.
- The steel HEM section of the experimental tests (section 3.7 and subsection 3.9.1) is replaced by an analytical rigid part with infinite stiffness, further named as rigid element.
- Lateral contraction is constrained to model with respect to the load introduction of the sandwich panel.
- 3D stress state do not influence results.

Moreover the input data of the numerical model and the assumptions are discussed in the following subsections.

4.1.1 Geometry

The sandwich panel depth (D) is arbitrary taken as 1,0 mm. The sandwich panel length (L) or sandwich panel height (h) refer to the (cubic) short sandwich panel of 150 mm or the large sandwich wall panel of 2650 mm (Figure 63). The sandwich panel face sheet thickness (t) varies by either 0,8 mm or 1,5 mm or 3,0 mm while the core has a thickness (c) of 150 mm plus two times the half face sheet thickness. Table 20 represents the average dimensions of the experimental tests. At the lower and upper part of the sandwich panel the load introduction condition provides the boundary conditions. The load introduction contains a hinge support and a roller support. A force at the roller support applies a compression load into the centre line of the sandwich panel. An extensive discussion about the boundary conditions will be given in subsection 4.1.4 to 4.1.5.

Table 20: Geometry average dimensions

<table>
<thead>
<tr>
<th>Average dimensions per face sheet</th>
<th>Unit</th>
<th>0,8 mm</th>
<th>1,5 mm</th>
<th>3,0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face sheet thickness (t)</td>
<td>[mm]</td>
<td>0,88</td>
<td>1,50</td>
<td>2,91</td>
</tr>
<tr>
<td>Core thickness (c)</td>
<td>[mm]</td>
<td>150,00</td>
<td>150,00</td>
<td>150,00</td>
</tr>
<tr>
<td>Depth short sandwich panel (D)</td>
<td>[mm]</td>
<td>150,65</td>
<td>149,14</td>
<td>149,24</td>
</tr>
<tr>
<td>Length short sandwich panel (L = h)</td>
<td>[mm]</td>
<td>149,86</td>
<td>150,04</td>
<td>150,08</td>
</tr>
<tr>
<td>Depth large sandwich panel (D)</td>
<td>[mm]</td>
<td>900,50</td>
<td>898,50</td>
<td>899,67</td>
</tr>
<tr>
<td>Length large sandwich panel (L = h)</td>
<td>[mm]</td>
<td>2650,88</td>
<td>2650,00</td>
<td>2331,0 or 2643,0</td>
</tr>
</tbody>
</table>

4.1.2 Element types

Element studies on the core and face sheet of a sandwich panel were performed individually. The element behaviour agrees to the analytical buckling behaviour of either the face sheets or core. The thin face sheets have to perform accurately in compression and bending. Due to the slender geometry the Euler-Bernoulli theory is valid. A B23 (beam) element with a 2-node cubic interpolation function satisfies. A B23 element has three degrees of freedom (DOF) per node. Each node has two in-plane translational DOF’s, i.e. U1 and U2, and one rotational DOF named UR3. The core has to perform well in compression, tension, bending and shear. The 2D representation of the core results in a continuum element with plane stress capabilities from the assumption that the 3D stress state do not influence results. The plane stress condition assumes no stresses in the z-direction across the depth of the sandwich panel.
From the CPU time (process time), the simulation time is faster with two times the amount of CPS4 elements compared to CPS8 elements. With respect to face sheet wrinkling behaviour the thickness of the face sheet determines the large amount of core elements (see section 4.1.7). Therefore, the accurateness of CPS4 to CPS8 elements are similar. CPS4 element will be used. These CPS4 elements have 4-nodes with two translational DOF’s per node (U1 and U2) and a fully integrated first order interpolation function.

4.1.3 Material behaviour

Elastic material behaviour is applied to the core and face sheet material. Both materials are assumed to behave isotropic with a modulus of elasticity and Poisson ratio according to the measurements of the experimental tests (Table 21). The compression properties of the face sheet are obtained from test type 5 in section 3.7.

Table 21: Material properties FEM model

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>0.8 mm</th>
<th>1.5 mm</th>
<th>3.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core modulus of elasticity ($E_c$)</td>
<td>[ Mpa ]</td>
<td>28</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Core poison ratio ($\nu_c$)</td>
<td>[-]</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Face sheet modulus of elasticity ($E_f$)</td>
<td>[ Mpa ]</td>
<td>9924</td>
<td>7218</td>
<td>6679</td>
</tr>
<tr>
<td>Face sheet poison ratio ($\nu_f$)</td>
<td>[-]</td>
<td>0.37</td>
<td>0.10</td>
<td>0.27</td>
</tr>
</tbody>
</table>

4.1.4 Constraints

To model the connections between the face sheet, core and rigid element several constraints are used. The assumed conditions of the enclosed face sheets by a HEM section used in test 5 (section 3.7 figure 29) are unable to use in an eigenvalue analysis. In the experimental test the face sheets were enclosed by the HEM section to prevent lateral deformations due to the load introduction into the test specimen. In the experimental test the lateral deformations of the sandwich panel due to lateral contraction of the specimen were constrained, while the sandwich panel was able to shrink.

To apply similar conditions to the FEM model a nonlinear constraint behaviour is required to model compression and no tension at the face sheets that were enclosed by the HEM section. However, nonlinear equations are linearized in an eigenvalue analysis. Therefore the lateral contraction of the sandwich panel at the rigid element is constraint to both translational d.o.f’s (U1 = U2 = 0). To prevent shear mode instabilities in the model the rotational DOF (UR3 = 0) of the beam element is also constrained to the rigid element.

From the experimental tests it is found that the glue connection between the face sheet and core does not fail and will be assumed to be rigid. To connect the core to the face sheet and to the rigid element two types of constraints are required. The constraints are limited by the constraint conditions and the conditions of an eigenvalue analysis. Two surface-to-surface tie constraints and two coupling constraints provide a kinematic coupling between the different parts (See location constraints in figure 64).
A kinematic coupling between parts can contain two translational DOF (U1 and U2) and one rotational DOF (UR3). A simplification of the experimental test setup is required to apply proper boundary conditions in the numerical model. The surface-to-surface tie constraints between the face sheet and core fix the translations U1 and U2. At the supports the end node of the two face sheets and the edge of the core are fixed to the rigid element with a coupling constraint. The boundary conditions of the coupling constrained are set to U1 = U2 = UR3 = 0. The face sheet B23 element is modelled by a wire that represents the face sheet centre line. The core material has a thickness of 150 mm. To attach the core to the face sheet by a tie constraint the core thickness is stretched by two times the half face sheet thickness. The core edge can be attached to the centre line of the face sheet without a gap. The conditions of the surface-to-surface tie constraint are:

- The mesh size of the slave surface (face sheet) needs to be equal or smaller than the mesh size of the master surface (core).
- The master and slave surface are assigned to the core and face sheet with respect to the bending stiffness ratio of these materials.
- A node cannot be used by two kinematic coupling definitions and a slave surface or slave node cannot be used twice.

The latter causes an overconstraint at the face sheet end nodes. These nodes are used in the tie constraint and the coupling constraint. The tie constraints are automatically removed at these nodes. Other warnings during the simulation are negligible small adjustments between the face sheet slave and core master surface of 2.22*10^-16 mm or smaller. The tie constraint uses a linear equation to describe the kinematic coupling. The position tolerance of the surface-to-surface tie constraint is set to default.

4.1.5 Boundary conditions

The constraints provide the connections between the face sheet and core. The rigid element provide the boundary conditions for the connection between the sandwich panel and the ground. An explanation of the boundary conditions are given for the short and long sandwich panels. The upper part of the short sandwich panel is constrained by a roller support at the rigid element. Translations in the x-direction are fixed (U1 = 0) and translations
in the y-direction are unconstraint (U2 = free). The lower rigid element is constrained by a hinge connection over the complete width (Figure 65). Translations in x-direction and y-direction are constrained (U1 = U2 = 0).

Figure 65: Left: Short sandwich panel with system length (L) 150 mm. Right: Large sandwich panel with system length (L) 2650 mm.

The upper part of the large sandwich panel is constrained by a roller support at the rigid element. Translations in the x-direction are fixed (U1 = 0) and translations in the y-direction are unconstraint (U2 = free). The lower rigid element is constrained by a hinge connection. Translations in x-direction and y-direction are constrained (U1 = U2 = 0). Both supports contain a rotational spring stiffness (Kr) which will be discussed in section 4.5.1.

4.1.6 Load

A point load is applied to the upper rigid (Figure 65). The rigid element spreads the point load to a uniform distributed load into the sandwich panel. Due to the rigid element the behaviour of a point load is similar to a uniform distributed load. To perform the eigenvalue analysis a unit load of one Newton is applied in the negative y-direction (F2 = -1 N). The geometrical non-linear analysis is deformation controlled by a translation in the negative y-direction (U2). This translation is equal to the maximum axial shortening measured in each sandwich panel test.

4.1.7 Mesh size sensitivity analysis

Buckling modes vary by either shear buckling, Euler buckling, wrinkling or coupled instabilities. The numerical model must be able to simulate all these buckling modes independent of the mesh size. Parameters that contribute to a correct mesh size are given in figure 66 dependant on the mesh width or height. The system lengths of short sandwich panels (150 mm) and large sandwich panels (2650 mm) are examined.
The main parameters (Appendix I) that will be discussed are:

- Core mesh width;
- Wrinkling wave length;
- Mesh height.

**Core mesh width**

The mesh size of the core thickness affects sandwich panel shear buckling. A sandwich panel with thin face sheets has a larger contribution to affect the amount of elements than thick face sheets. A CPS4 core mesh size of 5.0 mm over the width satisfies to a system length of 150 mm while a core mesh size of 15.0 mm over the core width satisfies to system lengths of 2650 mm (Appendix I). From system lengths of 2650 mm it is clear that the core mesh width and face sheet thickness have no influence to the Euler buckling mode or wrinkling mode. To both system lengths the following conditions are valid:

- The mesh distribution over the core thickness is symmetric.
- An element length ratio of 1:3 is assumed. Larger element ratios than 1:3 might cause inaccurate results.
- A mesh of either CPS8 or CPS4 elements satisfies.

**Wrinkling**

Wrinkling half sine wave length ($L_w$) can be described by Allen [8] according to a conservative approximation formula in section 2.5. The wrinkling wave length is a function of the face sheet modulus of elasticity ($E$) and the face sheet thickness ($t$) while the core parameters are treated as constants. According to the continuous lines of the diagram of figure 67 the face sheet thickness has a larger influence to the sine wavelength than the face sheet modulus of elasticity. The square blocks in the same figure represent the modulus of elasticity of the three sandwich panel face sheet thicknesses. From the experimental tests (Section 3.7) the wave lengths are added to figure 67 and are marked by triangles. The wrinkling sine wave length of the experimental tests represent the lower boundaries.
Figure 67: The continuous line represents the sine wavelength according to the formula of Allen. Square blocks refer to the actual modulus of elasticity of a specific face sheet thickness. Triangles represent the wavelength of the experimental tests.

The wrinkling sine wavelength of the core can be described by CPS4 elements or CPS8 elements. A CPS4 element has a linear interpolation function and is able to simulate a sine wavelength by four elements, while a CPS8 element with a quadratic interpolation function is capable of describing the same sine wavelength by two elements. The lower boundaries wave length and the CPS element distribution result in the maximum mesh height to describe the wavelength by CPS4 or CPS8 elements according to Table 22.

Table 22: Mesh size to describe sine wavelength with CPS4 coarse dashed black line and CPS8 fine dashed blue line.

<table>
<thead>
<tr>
<th>Sine wavelength (2*Lw) [mm]</th>
<th>Mesh height CPS4 [mm]</th>
<th>Mesh height CPS8 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFRP 0.8 mm</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>GFRP 1.5 mm</td>
<td>30</td>
<td>7.5</td>
</tr>
<tr>
<td>GFRP 3.0 mm</td>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>

**Mesh height**

The tie constraint condition assumes that the face sheet mesh size matches the core mesh size. Furthermore, the mesh over the system length is constant to result in a symmetric mesh distribution. At an increasing amount of elements over the system length the buckling load of the first mode converges to less than one percent of the analytical reference load regardless of the face sheet thickness. It is important to emphasize that the buckling load to thin face sheets converges slower than to thick face sheets. At system lengths of 150 mm and 2650 mm mesh heights are 1.5 mm and 40 mm respectively (Appendix I). The mesh size of 1.5 mm is smaller than the mesh size given in Table 22. The model with a system length of 2650 mm must be able to simulate wrinkling too. Wrinkling requires a finer mesh than Euler buckling. The mesh sizes of the wrinkling wave length (Table 22) are smaller than the 40 mm mesh height. Besides, the accuracy of the buckling load of the wrinkling wave length mesh sizes are smaller than one percent of the analytical Euler buckling load.
A model that has to describe Euler buckling but also wrinkling is restricted to the mesh height determined by the wrinkling wavelength. The mesh height of 150 mm system length is 1.5 mm while the mesh height of 2650 mm system length satisfies to table 22. These mesh heights are valid to mesh sizes of the core and face sheet.

Conclusion

In general, it can be concluded that the mesh width and height depends on the face sheet thickness, system length and critical buckling mode. The system length and buckling mode are related. With respect to the first buckling mode distinguishes the system length the modes by wrinkling and Euler buckling (Figure 70). Up to a system length of 1500 mm wrinkling dominates the mesh size and beyond 1500 mm Euler buckling dominates the mesh size. Nevertheless, the second buckling mode is wrinkling regardless of the system length.

The mesh sensitivity analysis is valid to sandwich panels with relative thin face sheets. Sandwich panels with thick face sheets use a different mesh distribution but the approach to determine the mesh size remains similar to sandwich panels with thin face sheets. The minimum mesh sizes are used with respect to the assumed element length ratio of 1:3. An element ratio of one will be assumed to system lengths of 150 mm and 1:3 to system lengths of 2650 mm. This results in the mesh sizes given in table 23.

Table 23: Mesh size core and face sheet dependant to the system length and face sheet thickness.

<table>
<thead>
<tr>
<th>System length (L) [mm]</th>
<th>Face sheet thickness (t) [mm]</th>
<th>CPS4 width (mscx) [mm]</th>
<th>CPS4 height (mscy) [mm]</th>
<th>B23 (msf) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>variable</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>2650</td>
<td>0.8</td>
<td>15</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>15</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>15</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Note that the mesh sensitivity analysis has been performed to CPS4 elements and CPS8 elements. Regardless of the computational time the CPS8 elements perform even better than CPS4 elements. To prevent an extensive mesh study and provide a reliable approximation of different buckling modes CSP8 elements can be used instead of CPS4 elements with half the amount of elements.

4.1.8 Python script

Two python scripts (Appendix M) contain the input data to execute the analysis. The first script contains an eigenvalue buckling analysis and the second script executes a geometrical non-linear analysis by assigning an imperfection from the buckling mode provided from the analysis of the first script. Therefore, keywords are included in both scripts. The input data is written in the form of variables. The first variable in both scripts is the model name. The model name refers to a face sheet thickness. Each name automatically assigns a set face sheet material properties of the chosen face sheet thickness. Other variables are the system length, core material properties, mesh size, and iteration steps.

4.2 SOLVING

4.2.1 Analysis and solution method

After the initial step follows a linear perturbation buckle step by which a linear buckling analysis (LBA), i.e. eigenvalue analysis, is carried out on the sandwich panel. The model response of an eigenvalue buckling analysis is defined by the linear elastic stiffness in the initial state. Plasticity or geometrical nonlinearities are ignored. An eigenvalue is a
non-unique solution and is the multiple ($\lambda$) of the applied load that causes different buckling modes. The point at which buckling occurs is the bifurcation point. Close to this point the total stiffness matrix (first term of formula (XXI)) becomes singular and results into the eigenvalue ($\lambda$) according to the equation of the eigenvalue problem:

$$
([K_0] - \lambda [K_G]) [u] = 0
$$

(XXI)

The minus sign in the first term of the formula refers to a compression load on the sandwich panel. The second term ($u$) represents the buckling mode shapes or eigenvectors. The eigenvalue buckling analysis is used to estimate the critical buckling loads of the sandwich panel at the corresponding buckling mode shapes (eigenvectors). The buckling mode shapes are normalised vectors and represent a normalised maximum displacement of 1,0 at the critical buckling load. A buckling mode is a prediction of the most obvious failure mechanism. To perform an eigenvalue buckling analysis with two eigenmodes the Subspace iteration method can be used with 20 vectors per iteration and a maximum of 150 iterations regardless of the face sheet thickness or sandwich panel length. The Subspace iteration method is faster than the Lanczos solver with less than 20 requested eigenmodes.

Figure 68: Schematic representation analysis

After the linear perturbation buckle step (Figure 68) the analysis continues by a general static step to perform a geometrical nonlinear analysis with imperfections (GNIA). The analysis uses a Full Newton-Rhapson solution technique (Figure 69) to solve the nonlinear equilibrium equations.

Figure 69: Schematic representation of the Newton-Rhapson iterative method [47].
A load control method such as Riks is inappropriate to model local instabilities like face sheet wrinkling or local buckling. Therefore, the load is applied as a translation (displacement control) to the top hinge of the sandwich panel in the negative y-direction (U2) in a general static step to model both instability types. The general static step includes effects of geometrical nonlinearities by adding an initial imperfection or amplitude of the eigenvalue analysis to the geometry of the initial state. The imperfection ($\Delta x_i$) can be described by formula (XXII) with an eigenvalue mode shape of 1.0 ($\phi_i$) and associated scale factor ($w_i$). The imperfection applies a nodal displacement to the geometry of the initial state by:

$$\Delta x_i = \sum_{i=1}^{M} w_i \phi_i$$  

(XXII)

### 4.2.2 Analytical and numerical buckling behaviour hinged system

Figure 70 shows results of mode one in a LBA with three different face sheet thicknesses and length. The solid hatch under the continuous line marks per face sheet thickness the safe area of a sandwich panel loaded in compression. It is obvious that above the continuous line dominates the unsafe area. According to the literature the wrinkling formula of Allen [8] is a conservative outcome of the buckling load. This clarifies the small difference between the analytical wrinkling load and the LBA as can be seen in the same figure. As soon as the buckling length is beyond the coupled instabilities length the buckling load equals the Euler buckling load. At Euler buckling the LBA and analytical analysis (Section 2.5) gives similar results. The overall buckling behaviour can be distinguished by wrinkling and Euler buckling. Wrinkling occurs at short sandwich panel lengths, while Euler buckling dominates at large sandwich panel lengths. At the transition from wrinkling to Euler buckling the linear buckling analysis (LBA) changes from wrinkling mode one to Euler buckling mode one.

![LBA mode one of sandwich panel with depth of 900 mm. Wrinkling case II refers to asymmetrical wrinkling.](image)

Figure 70: LBA mode one of sandwich panel with depth of 900 mm. Wrinkling case II refers to asymmetrical wrinkling.
It can be emphasized that the buckling behaviour model is dedicated to a sandwich wall panel with hinges at both ends and a depth of 900 mm. The assumption of a hinged system without a rotational spring stiffness at both ends is a safe assumption to model the buckling behaviour of a sandwich panel.

4.3 MODEL VALIDATION

Two numerical models will be treated. A FEM model that describes the axial stiffness response of a short sandwich panels with initial imperfections. This FEM model validates experimental test 5. The second model discuss the buckling behaviour of the large sandwich panels with initial imperfections applied to the buckling modes. This second model validates experimental test 6. To verify the numerical model a benchmark is given in Appendix J with similar material properties of the face sheet and core. This model is verified by an analytical calculation of a homogeneous cross section with the same dimensions as the sandwich panel.

4.4 VALIDATION FE MODEL SHORT PANELS TEST 5

In the experimental research of test 5 the load introduction conditions and the axial stiffness of a short sandwich panel loaded in compression were examined. The axial stiffness behaviour of the short sandwich panel is used to derive the face sheet compression modulus of elasticity. The axial stiffness behaviour of the experimental tests will be validated in this section by a numerical model conform a GNL analysis. The GNL analysis includes imperfections of the first and second buckling mode. The input data of the GNL analysis is given in table 24. Since it is not possible to present all diagrams of the axial stiffness behaviour per face sheet thickness, relevant notes will be given. Other face sheet thicknesses are given in Appendix K.

Table 24: Input data GNL analysis per face sheet thickness

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>0,8 mm</th>
<th>1,5 mm</th>
<th>3,0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial displacement</td>
<td>[ mm ]</td>
<td>-2,3</td>
<td>-2,3</td>
<td>-2,2</td>
</tr>
<tr>
<td>Max. number of increments</td>
<td>[- ]</td>
<td>150</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Initial increment</td>
<td>[ - ]</td>
<td>0,005</td>
<td>0,005</td>
<td>0,0005</td>
</tr>
<tr>
<td>Min. increment</td>
<td>[ - ]</td>
<td>1,0E-07</td>
<td>1,0E-07</td>
<td>1,0E-07</td>
</tr>
<tr>
<td>Max. increment</td>
<td>[ - ]</td>
<td>0,02</td>
<td>0,02</td>
<td>0,02</td>
</tr>
</tbody>
</table>

The axial stiffness response of a sandwich panel with face sheets of either 0,8 mm or 1,5 mm or 3,0 mm depends on two main features:

- Geometrical imperfections;
- Face sheet modulus of elasticity.

The geometrical imperfections are assigned to the buckling modes of the eigenvalue analysis. Table 25 contains all performed FE analysis’s with the assigned imperfections.
Table 25: Performed analysis's

<table>
<thead>
<tr>
<th>Face sheet</th>
<th>Variable</th>
<th>Unit</th>
<th>Analysis's</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,8 mm</td>
<td>Mode n1=n2</td>
<td>[ mm ]</td>
<td>0,088 0,22 0,44 0,66 0,88</td>
</tr>
<tr>
<td>0,8 mm</td>
<td>E*</td>
<td>[ MPa ]</td>
<td>5650 6947 7932 8932 9924</td>
</tr>
<tr>
<td>1,5 mm</td>
<td>Mode n1=n2</td>
<td>[ mm ]</td>
<td>0,001 0,005 0,01 0,05 0,1</td>
</tr>
<tr>
<td>1,5 mm</td>
<td>E*</td>
<td>[ MPa ]</td>
<td>5052 5415 5900 6135 7218</td>
</tr>
<tr>
<td>3,0 mm</td>
<td>Mode n1=n2</td>
<td>[ mm ]</td>
<td>0,001 0,01 0,05 0,1 0,3</td>
</tr>
<tr>
<td>3,0 mm</td>
<td>E*</td>
<td>[ MPa ]</td>
<td>5343 5677 6011 6345 6679</td>
</tr>
</tbody>
</table>

$E^* = \text{Compression modulus of elasticity face sheet.}$

$n1=n2$ refers to both wrinkling modes.

Independent of the face sheet thickness both eigenmodes of the eigenvalue analysis result in wrinkling (Table 26). The buckling modes refer to the wrinkling modes of section 2.5. Face sheet wrinkling is a local instability mode. The magnitude of the geometrical imperfections are determined in an imperfection sensitivity analysis (Appendix K).

Table 26: Buckling modes and loads

<table>
<thead>
<tr>
<th>Face sheet thickness</th>
<th>0,8 mm</th>
<th>1,5 mm</th>
<th>3,0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_0$, Magnitude</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+1,000+00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+9,167+00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+6,333+00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+7,500+00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+6,667+00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+5,000+00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+4,167+00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+3,333+00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+2,500+00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+1,667+00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+6,333+00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+0,000+00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Eigenmode 1**

Buckling mode: Wrinkling case I
Buckling load: 35,15 kN

Buckling mode: Wrinkling case I
Buckling load: 53,08 kN

Buckling mode: Wrinkling case II
Buckling load: 105,09 kN

In general, the imperfection sensitivity analysis concludes that thin face sheets of 0,8 mm are more sensitive to geometrical imperfections than thicker face sheets. And independent of the face sheet thickness, the contribution of these imperfections to the axial stiffness behaviour of the force-axial shortening diagram in the end region (Figure 71, Region B) is larger than in the initial region (Figure 71, region A). Local geometrical imperfections in the face sheet surface were not observed during the experimental tests.
Therefore these imperfections (Table 27) are assumed by ratio to the face sheet thickness and according to the axial stiffness response of the experimental tests showed in the force-axial shortening diagrams (Appendix K). Note that a small initial imperfection indicates a perfect linear geometry.

Table 27: Geometrical local imperfections assigned to the buckling modes of wrinkling

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>0.8 mm</th>
<th>1.5 mm</th>
<th>3.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average thickness face sheet</td>
<td>mm</td>
<td>0.88</td>
<td>1.5</td>
<td>2.91</td>
</tr>
<tr>
<td>Geometrical imperfection mode</td>
<td>mm</td>
<td>0.088</td>
<td>0.001</td>
<td>0.05</td>
</tr>
<tr>
<td>Percentage ratio</td>
<td>%</td>
<td>10</td>
<td>0.07</td>
<td>1.72</td>
</tr>
</tbody>
</table>

Then, the second feature that influences the axial stiffness of the sandwich panel is the face sheet modulus of elasticity. Comparing the axial stiffness of the core material (AE) with a depth of 1 mm to two face sheets (2AE) result in the axial stiffness ratios of table 28. The face sheet modulus of elasticity contribution to the axial stiffness of the sandwich panel is larger than the stiffness contribution of the core material. If the face sheet thickness increases, increases the axial stiffness ratio of the face sheet over the core.

Table 28: Axial stiffness ratio face sheets to core material. The panel depth is normalised over a thickness of 1.0 mm.

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>0.8 mm</th>
<th>1.5 mm</th>
<th>3.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial stiffness two face sheets</td>
<td>N</td>
<td>15878</td>
<td>21654</td>
<td>40074</td>
</tr>
<tr>
<td>Axial stiffness core (AE)</td>
<td>N</td>
<td>4500</td>
<td>4500</td>
<td>4500</td>
</tr>
<tr>
<td>Axial stiffness ratio</td>
<td>-</td>
<td>3.5</td>
<td>4.8</td>
<td>8.9</td>
</tr>
</tbody>
</table>
From the force-axial shortening diagram (Figure 72) is observed that the slope that represents the axial stiffness of the sandwich panel is stiffer in the FE-analysis than the experimental tests. Furthermore, the initial stiffness of the experimental tests change in the initial toe region of the same diagram due to the load applied on the specimen. Skewness of the sandwich panel is not included in the FE-analysis.

![Diagram](image)

**Figure 72: Force-axial shortening diagram (face sheet thickness 1,5 mm). Continuous lines are the experimental tests and the dotted lines represent the FEM GNL analysis with a varying face sheet modulus of elasticity.**

The overestimation of the axial stiffness of the GNL model is caused by a conservative assumption. A lower face sheet modulus of elasticity affects the complete axial stiffness presented in the diagram. The GNL model assumed that the face sheet compression modulus of elasticity is equal to the tension modulus of elasticity. Lowering the face sheet modulus of elasticity by the percentages given in Table 29 results in the same axial stiffness as the experimental tests. A lower face sheet modulus of elasticity results in a better approximation of the axial sandwich panel stiffness than increasing the initial imperfection.

**Table 29: Face sheet compression modulus of elasticity**

<table>
<thead>
<tr>
<th>Face sheet thickness (t)</th>
<th>Experimental test [MPa]</th>
<th>FEM [MPa]</th>
<th>Reduction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>t = 0,8 mm</td>
<td>9924</td>
<td>8932</td>
<td>10,0</td>
</tr>
<tr>
<td>t = 1,5 mm</td>
<td>7218</td>
<td>5900</td>
<td>18,3</td>
</tr>
<tr>
<td>t = 3,0 mm</td>
<td>6679</td>
<td>6345</td>
<td>5,0</td>
</tr>
</tbody>
</table>
4.4.1 Discussion

The main objective of the load introduction cubic sandwich panel test (short sandwich panel) was to examine the load introduction conditions at the top edge of the sandwich panel and to give an indication of the compression properties of the GFRP face sheets.

The load introduction conditions of the experimental tests were different. In the experimental tests a steel section encloses the lower and upper part of the sandwich panel over a height of 25 mm (Figure 73). Due to restrictions (linearization of nonlinear behaviour) of an eigenvalue calculation are similar load conditions to the experimental tests unable to simulate. The FEM model underestimates the buckling behaviour of the experimental tests. The axial stiffness behaviour found in the FEM model is an underestimation. A reduction of the face sheet modulus of elasticity is acceptable.

The assumption of a similar modulus of elasticity in compression and tension in the numerical model is an overestimation of the axial stiffness behaviour and can be rejected. The compression modulus of elasticity is lower than assumed. According to the face sheet thickness of 0,8 mm or 1,5 mm or 3,0 mm the face sheet compression modulus of elasticity is reduced to similar behaviour as found in the experimental tests.

Figure 73: Left: Specimen experimental test enclosed by steel HEM section. Right: FE-model without lateral support (0,8 mm face sheets).

The total height of the sandwich panel is 150 mm. The panel is enclosed over two times 25 mm. This lateral support decreases the buckling length and increases the buckling load. Buckling modes change too. Without a lateral support of the sandwich panel occur local face sheet instabilities or wrinkling rather to thin face sheets of 0,8 mm than thicker face sheets.

Independent of the face sheet thickness results the buckling mode in wrinkling. Face sheet wrinkling rigid base case I is dominant to thin face sheets of 0,8 mm and 1,5 mm. At thicker face sheets of 3,0 mm face sheet wrinkling asymmetrical case II or symmetrical case III dominates over face sheet wrinkling of case I.

Imperfections are assigned to the buckling modes. With respect to the imperfection sensitivity analysis (Appendix K) is found that thin face sheets of 0,8 mm are more imperfection sensitive than thick face sheets of 1,5 or 3,0 mm. A slightly larger imperfection changes the initial axial stiffness significant but also changes the curve of the force-axial shortening.

Imperfections of a skew geometry are not included in the FE-analysis. According to the experimental tests are small differences observed in the length of the outer face sheets of a sandwich panel. The compression force in the shorter
face sheet is larger than the compression force in the opposite taller face sheet length of a skew specimen. It is obvious that face sheet wrinkling case I occurs rather than case II or case III in the shorter and more compressed face sheet of a skew specimen. A lower buckling load is obvious to face sheet wrinkling rigid base case I.

4.4.2 Conclusion

In general, from the FE-analysis of the short sandwich panel is concluded:

− Thin face sheets of 0,8 mm are more sensitive to wrinkling than thicker face sheets of 1,5 and 3,0 mm.
− The sandwich panel axial stiffness is variable by the geometrical imperfection assigned to the buckling mode and the face sheet modulus of elasticity.
− By ratio of the assigned imperfection to the face sheet thickness has a sandwich panel with thin face sheets of 0,8 mm a larger assigned imperfection than thicker face sheets.
− The thicker the face sheet, the larger the contribution of a face sheet to the axial stiffness of the sandwich panel is.
− Restrictions of an eigenvalue analysis (linearization of nonlinear behaviour) constrain the possibilities to simulate similar load conditions as used in the in the experimental tests.
− Due to the sandwich panel geometry with a length-width ratio of approximate one results the first and second buckling mode in wrinkling.
− The two buckling modes of sandwich panels with face sheets of 0,8 mm and 1,5 mm result in face sheet wrinkling case I and face sheets of 3,0 mm results in face sheet wrinkling case II and case III.

The assumption of an equal modulus of elasticity in compression and tension for face sheets overestimates the axial stiffness behaviour. A reduction of 5-18% of the tensile face sheet modulus of elasticity is acceptable.
4.5 FE MODEL LARGE PANELS TEST TYPE 6

In the experimental research of test type 6 the stability of a sandwich wall panel is examined. Depending on the face sheet thickness wrinkling, global buckling or coupled instabilities are observed. An explanation of the buckling behaviour observed in the sandwich wall panel tests will be given in accordance with a FE-analysis. Important features of the analysis that will be treated are:

- Boundary conditions;
- Buckling mode;
- Buckling load;
- Geometrical imperfections.

4.5.1 Boundary conditions

By performing a LBA of a hinged sandwich panel the buckling load results in an underestimation of the buckling load with respect to buckling loads of the experimental tests (Figure 74). Except to sandwich panels with face sheets of 0.8 mm. The ultimate load of a sandwich panel with face sheets of 0.8 mm is significantly lower than the FEM eigenvalue compared to thicker face sheets of 1.5 and 3.0 mm. This buckling behaviour seems odd but can be logically explained.

Figure 74: Experimental tests and FEM eigenvalues with a rotational spring stiffness of zero.
From the experimental tests it is known that the round steel rod is completely fixed to either the actuator or the load cell (Figure 75). In figure 76 at the left, the gap between the bolt (attached to the HEM section) and the round steel rod is assumed in the order of 0.1 millimetres. When the applied force at the support is equal to zero point (c) at the bolt makes no contact with point (d) at the round steel rod. At an increasing load the HEM section is able to rotate freely around point (A) till the gap is closed and contact between points (c) and (d) occurs.

Figure 76 at the right, if contact occurs at point (c, d) the HEM section is only able to rotate over the circumference of the round steel rod at point (A) due to friction. Friction occurs between the surface of the HEM section and the round steel rod. The normal force ($F_2$) perpendicular to the surface of the rod times a friction coefficient ($\mu$) results in a friction force ($F_w$) parallel to the friction surface. A steel to steel static friction coefficient ($\mu$) of 0.5 to 0.8 is assumed. The contribution of the friction force multiplied by a constant radius of the rod ($r_1 = 25$ mm) results in a resistance force couple ($M\mu$) described by equation (XXIII):
\[ M_\mu = F_2 \cdot \mu \cdot r_1 \]  

(XXIII)

The friction coefficient and the rod radius are both constants while the normal force \((F_2)\) is a variable. The normal force depends on the applied compression load on the sandwich panel. The force couple has a positive contribution to the bending behaviour of the sandwich panel. The behaviour of the force couple and rotation represents a moment-rotation diagram (Figure 77). The ratio of the moment over the rotation expresses a nonlinear rotational spring stiffness \((K_r)\) in the connection.

![Moment-rotation diagram](image)

Figure 77: Left: Moment-rotation diagram. The increase of the rotation between point \((c)\) and point \((d)\) represents the rotation over the gap. The ratio \(K_r\) is the rotational spring stiffness. Middle: Hinged system. Right: Fully clamped system.

At point \((c)\) the rotation and moment are zero (Figure 77 at the left). While the gap closes, the rotation increases from point \((c)\) to point \((d)\) and the system behaves as a hinged system (Figure 77 at the middle). After point \((d)\) the force couple is activated due to friction. Both, the force couple and rotation will increase but the slope and linear or nonlinear behaviour are unknown. If the moment-rotation relation follows the horizontal dashed line (Figure 77 at the left) the rotational spring stiffness is zero and equals to a hinged system (Figure 77 at the middle). If the moment-rotation relation follows the vertical dashed line (Figure 77 at the left) the rotational spring stiffness is infinite and equals to a fully clamped system (Figure 77 at the right).

Nevertheless, the rotational spring stiffness is unable to determine due to two unknown variables, i.e. the normal force \((F_2)\) and the rotation \((\phi)\). To simulate a nonlinear rotational spring stiffness with a static or dynamic frictional coefficient in a GNL contact interaction analysis is considered to be out of scope. A linear buckling analysis (LBA) linearizes the nonlinear rotational spring stiffness behaviour. Nonlinear behaviour is ignored and contact conditions are fixed in a LBA. The LBA will result in an overestimation of the buckling loads, buckling mode and will never be able to simulate the buckling behaviour of the experimental tests.

However, to explain the buckling of the experimental tests the rotational spring stiffness is assumed to be linear elastic (Table 30). The thicker the face sheet thickness the larger the contribution of the rotational spring stiffness to the buckling behaviour will be. The assumed rotational spring stiffness’s \((K_r)\) are determined in the rotational spring stiffness analysis of Appendix H. A simplified model with a linear rotational spring stiffness results in ‘a solution’ but will never meet the conditions mentioned above to simulate the exact buckling behaviour of the experimental tests.
Table 30: Rotational spring stiffness supports

<table>
<thead>
<tr>
<th>Specimens</th>
<th>S6-00</th>
<th>S6-02</th>
<th>S6-03</th>
<th>S6-04</th>
<th>S6-05</th>
</tr>
</thead>
<tbody>
<tr>
<td>S6-00</td>
<td>3,0</td>
<td>3,0</td>
<td>1,5</td>
<td>0,8</td>
<td>0,8</td>
</tr>
<tr>
<td>S6-02</td>
<td>3,94 E+08</td>
<td>2,25 E+08</td>
<td>6,15 E+07</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### 4.5.2 Buckling mode

A hinged system without a rotational spring stiffness results in Euler buckling to the first buckling mode and the second buckling mode results in wrinkling (Figure 78).

Hinged system with rotational spring stiffness of zero.

Buckling mode 1: Euler buckling. Deformation scale factor 100.

Buckling mode 2: Wrinkling and zoomed view of middle sandwich panel. Deformation scale factor 5.

Figure 78: Buckling modes of a hinged sandwich panel with rotational spring stiffness of zero.

### 4.5.3 Buckling load

As mentioned earlier, the ultimate load of sandwich panels with 0,8 mm face sheets is lower than the eigenvalue. Sandwich panels with 0,8 mm face sheets are constrained by a rotational spring stiffness of zero ($K_r = 0$) in a hinged system (Figure 79, left). To estimate the buckling load of sandwich panels with 0,8 mm face sheets the buckling
length is assumed to be equal to the system length. Therefore, the first and second buckling mode represent respectively Euler buckling and wrinkling.

![Diagram](image)

Figure 79: Left: Hinged system with rotational spring stiffness equals zero. Right: Fully clamped system with infinite rotational spring stiffness.

With respect to a fully clamped system (Figure 79 right) the buckling length is equal to: $L_{cr} = 0,5 \, L$. The rotational spring stiffness is infinite. The first and second buckling mode are both wrinkling. Wrinkling occurs rather than Euler buckling. The magnitude of the rotational spring stiffness determines which buckling mode occurs.

Sandwich panels with 1,5 and 3,0 mm face sheets contain a rotational spring stiffness of $0 > Kr > \text{infinite}$. A hinged system with rotational spring stiffness's according to figure 79 results in Euler buckling and wrinkling respectively buckling mode one and mode two. The critical buckling length is given by the range $0,5L < L_{cr} < L$. Both, the hinged system and a fully clamped system results in the buckling behaviour given in Table 31.

Table 31: Buckling modes and loads with $Kr$ equal to zero or infinite.

<table>
<thead>
<tr>
<th>Unit</th>
<th>$Kr = 0$</th>
<th>$Kr = \infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mode 1</td>
<td>Mode 2</td>
</tr>
<tr>
<td>0,8 mm</td>
<td>[ kN ]</td>
<td>A; 114,2</td>
</tr>
<tr>
<td>1,5 mm</td>
<td>[ kN ]</td>
<td>A; 190,8</td>
</tr>
<tr>
<td>3,0 mm</td>
<td>[ kN ]</td>
<td>A; 241,2</td>
</tr>
<tr>
<td>3,0 mm (L = 2331 mm)</td>
<td>[ kN ]</td>
<td>A; 296,6</td>
</tr>
</tbody>
</table>

A.) Euler buckling mode
B.) Wrinkling mode symmetrical/asymmetrical

Euler buckling is only described in the first mode of a hinged system ($Kr = 0$). Other buckling modes result in wrinkling. Note that buckling mode two of a hinged system ($Kr = 0$) equals the buckling mode and load of a fully clamped system ($Kr = \infty$). The rotational spring stiffness affects the buckling length. Dependant to the buckling length dominates Euler buckling at $L_{cr} = L$ in the first buckling mode and wrinkling at $L_{cr} = 0,5 \, L$ in both buckling modes.
4.5.4 Geometrical imperfection envelope

Initial imperfections with respect to the first and second buckling mode are not measured in the experimental tests. An FE-analysis that estimates the exact behaviour cannot be achieved due to the restrictions of the support boundary conditions explained in subsection 4.5.1. Nevertheless, to highlight the importance of geometrical imperfections to the bending stiffness and axial stiffness an explanation will be given by schematised representations of both stiffness behaviours (Figure 80). These diagrams are applicable to hinged sandwich panels with an assumed linear rotational spring stiffness in the range of $0 > K_r > \infty$ or from subsection 4.5.1. Imperfections are assigned to the first and second buckling mode respectively Euler buckling and wrinkling.

Imperfections of $L/10000$ and $L/750$ represent the magnitudes of the Euler buckling mode by ratio to the system length ($L$). $L/10000$ is almost equal to zero. $L/750$ is assumed from construction tolerances of a comparable structural element, namely a steel column in a building storey [48]. The minimum and maximum imperfection of wrinkling mode 2 are given by ratio to the face sheet thickness. The minimum imperfection of 1% of the face sheet thickness ($t_f$) is almost zero. The maximum imperfection is assumed to 30% of the face sheet thickness ($t_f$). Both mode imperfection ranges show an envelope in the diagrams of figure 80. These imperfections are reasonable to describe the axial stiffness behaviour and the bending stiffness behaviour of sandwich panels with a face sheet of either 0.8 or 1.5 or 3.0 mm. Notes with respect to the stiffness behaviour are given to each diagram.

**Mode 1 = n1 = variable. Mode 2 = n2 = constant**

![Diagram](image)

(a) Imperfection mode 1 has a large influence to the bending stiffness.
(b) Envelope range from n1 is $L/10000$ to $L/750$.
(c) Imperfection mode 1 has a small influence to the axial stiffness.
(d) Imperfection mode 1 has no influence to the initial axial stiffness.
(e) Envelope range from n1 is $L/10000$ to $L/750$. 
Mode 1 = \( n_1 \) = constant. Mode 2 = \( n_2 \) = variable

(f) Imperfection mode 2 has a small influence to the bending stiffness.

(g) Envelope range from \( n_2 \) is 1% of \( t_f \) to 30% of \( t_f \).

(h) Imperfection mode 2 influences almost the complete axial stiffness.

(i) Imperfection mode 2 has no influence to the initial axial stiffness.

(j) Envelope range from \( n_2 \) is 1% of \( t_f \) to 30% of \( t_f \).

Figure 80: Schematic representation of the force-out-of-plane deformation diagrams and the force-axial shortening diagram with geometrical imperfections of mode 1 and mode 2. The diagrams are applicable to hinged sandwich panels with system length \( L \).

The envelope given in the diagrams can be used to express imperfections of mode 1 and 2 at sandwich panels with an arbitrary face sheet thickness. GNIA’s are performed with variable imperfections of both buckling modes, see Table 32. These analysis’s are conducted with maximum 150 increments, an initial increment of 0,005, a minimum increment of 1,0E-07 and a maximum increment size of 0,02.

Table 32: Overview of all GNIA analysis’s with imperfections of mode 1 and mode 2. \( k_1 \) = factor. \( L \) = system length.

\( t_f = 0,8 \text{ mm} \)

<table>
<thead>
<tr>
<th>Unit</th>
<th>GNIA’s of mode 1 (n1), with constant ( n_2 = 0,088 \text{ mm or 10% of } t_f ).</th>
<th>GNIA’s of mode 2 (n2), with constant ( n_1 = 1,5 \text{ mm or } L/1900 ).</th>
</tr>
</thead>
<tbody>
<tr>
<td>28500 14250 10000 7125 5700 4750 2850 1900 1425 1140 750</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0,1</td>
<td>0,2</td>
<td>0,3</td>
</tr>
</tbody>
</table>

\( t_f = 1,5 \text{ mm} \)

<table>
<thead>
<tr>
<th>Unit</th>
<th>GNIA’s of mode 1 (n1), with constant ( n_2 = 0,15 \text{ mm or 10% of } t_f ).</th>
<th>GNIA’s of mode 2 (n2), with constant ( n_1 = 1,5 \text{ mm or } L/1900 ).</th>
</tr>
</thead>
<tbody>
<tr>
<td>28500 14250 10000 7125 5700 4750 2850 1900 1425 950 750 712</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0,1</td>
<td>0,2</td>
<td>0,3</td>
</tr>
</tbody>
</table>

\( t_f = 3,0 \text{ mm}; \ L = 2650 \text{ mm} \)

<table>
<thead>
<tr>
<th>Unit</th>
<th>GNIA’s of mode 1 (n1), with constant ( n_2 = 0,3 \text{ mm or 10% of } t_f ).</th>
</tr>
</thead>
<tbody>
<tr>
<td>10000 750</td>
<td></td>
</tr>
<tr>
<td>0,3</td>
<td>3,5</td>
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</tbody>
</table>
STABILITY OF AXIALLY LOADED GFRP SANDWICH WALL PANELS

GNIA’s of mode 2 (n2), with constant n1 = 1,5 mm or L/1900.

\[ n2 \text{ in } \% \text{ of } tf \]

<table>
<thead>
<tr>
<th>n2 in % of tf</th>
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<tr>
<td>1</td>
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<td>30</td>
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\[ tf = 3,0 \text{ mm}; \quad L = 2330 \text{ mm} \]

GNIA’s of mode 1 (n1), with constant n2 = 0,3 mm or 10\% of tf.

\[ k_1 \]

- 10000
- 750

\[ n1 = \frac{L}{k_1} \]

- 0,2
- 3,1

GNIA’s of mode 2 (n2), with constant n1 = 1,5 mm or L/1550.

\[ n2 \text{ in } \% \text{ of } tf \]

<table>
<thead>
<tr>
<th>n2 in % of tf</th>
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4.5.5 GNIA of sandwich panels

An explanation of an imperfection envelope will be given in accordance to a sandwich panel with face sheets of 0,8 mm. Other face sheet thicknesses are given in Appendix L. The analysis is performed with respect to the first and second buckling mode. The first buckling mode represents Euler buckling and the second buckling mode wrinkling. The influence of these buckling modes to the buckling behaviour is briefly explained by figure 81 and figure 82.

Figure 81: Force-out-of-plane deformation diagram with variable amplitude first buckling mode and a face sheet of 0,8 mm

Sandwich panels with 0,8 mm face sheets might be independent of the rotational spring stiffness conditions, as mentioned earlier. Test results of a panels with 0,8 mm face sheets (S6-04 and S6-05) are enclosed by the imperfection envelope assigned to the Euler buckling mode (Figure 81). This envelope contain a range of L/10000 and L/750. If imperfections of the Euler buckling mode increase the bending stiffness decrease. The influence of
Euler buckling mode imperfections to the bending stiffness decrease when the face sheet thickness increases Appendix L. Increasing the imperfections result to a lower bending stiffness and a larger out-of-plane deformation.

From the axial stiffness behaviour (Figure 82) can be concluded that thin face sheets of 0.8 mm are more sensitive to geometrical imperfections of the wrinkling mode than thicker face sheets of 1.5 and 3.0 mm. At an increasing imperfection of the wrinkling mode the axial stiffness behaviour decrease. Imperfections in the order of 1-30% of the face sheet thickness represent an envelope which encloses the test results of S6-04 and S6-05. The influence of wrinkling mode imperfections to the axial stiffness decrease when the face sheet thickness increases (Appendix L). A lower axial stiffness results in a lower buckling load.

Imperfections of both instability modes are able to decrease the bending stiffness. Nevertheless, imperfections of the wrinkling mode only affect the axial stiffness significantly.

![Graph of Force vs. Axial Shortening](image)

**Figure 82:** Force-axial shortening diagram with variable amplitude second buckling mode and a face sheet of 0.8 mm.

### 4.5.6 Coupled instabilities

Coupled instabilities are observed in the FE model. For example in the sandwich panel with 3.0 mm face sheets (Figure 83). Out-of-plane deformations increase due to a second order effect. Compression stress localizations occur in the most compressed face sheet which cause face sheet wrinkling case I – rigid base. Coupled instabilities result in a significant stiffness loss and an axial shortening of the whole sandwich panel.
4.5.7 Discussion FE model

The main objective of the lateral buckling sandwich wall panel test was to examine the dominant buckling behaviour. To determine the dominant buckling behaviour from experimental tests is indistinct due to coupled instabilities. By using the FE model explanations of the sandwich panel an explanation to the buckling behaviour is found.

From sandwich panels with 0.8 mm is observed that failure occurs at a significant lower load level than thicker face sheets of 1.5 and 3.0 mm. From the experimental tests higher load levels are observed than the critical buckling loads of the FE-analysis. These higher load levels occur to sandwich panels with 1.5 and 3.0 mm face sheets (Figure 84). Apparently, the support conditions behave different than the assumed hinge connection. A fully clamped column gives an overestimation of the buckling load according to the force-out-of-plane deformation diagram (Figure 84). From the diagram can be concluded that the rotational spring stiffness must be in the range of zero to infinite. Thus, the buckling length will be in the range of $0.5L < L_{cr} < L$.

In a hinged system with buckling length ($L_{cr} = L$) the first and second buckling mode results in Euler buckling and wrinkling respectively. In a system with an infinite rotational spring stiffness both supports are fully clamped. In a fully clamped structure both buckling modes result in wrinkling.

Due a GNL contact effects in the supports boundary conditions are different than initially assumed. A rotational spring stiffness partly constrains the sandwich at both supports. Variable parameters which describe the rotational spring stiffness are the normal force and rotation. The friction coefficient needs to be assumed. To model the GNL contact behaviour of the supports requires a GNL contact interaction analysis with a static or dynamic frictional coefficient. Due to a variable normal force and rotation the rotational spring stiffness must be updated each increment in a GNL analysis. A contact interaction analysis is considered to be out of scope. Thus, a FE model that estimates the buckling load by a LBA will result in an underestimation of the buckling load. Restrictions of the LBA result in an analysis with geometric linear behaviour and linear elastic material behaviour.

Second order effects are observed in the nonlinear force-out-of-plane diagrams. Whether the second order effect dominates over wrinkling to decrease the bending stiffness is not observed from the numerical analysis due to the missing rotational spring stiffness’s of the hinge supports. The assumption of a linear rotational spring stiffness
results in ‘a solution’ of the buckling behaviour but will never satisfy the requirements to simulate the buckling behaviour of the experimental tests.

![Figure 84: Contribution of a rotational spring stiffness to the buckling load. Continuous lines represent the experimental tests of 1.5 and 3.0 mm face sheets. Dashed lines represent the FE-analysis of a rotational spring stiffness of either zero or infinite.](image)

The assumption of a linear rotational spring stiffness is used to construct force-out-of-plane deformation diagrams and force-axial shortening diagrams. The assumed rotational spring stiffness in the supports is an underestimation. Regardless of the magnitude of the rotational spring stiffness the influence of Euler buckling or wrinkling imperfections to these diagrams remain similar. Reasonable imperfections are:

- $L/10000$ and $L/750$ to the Euler buckling mode;
- 1-30% of the face sheet thickness to the wrinkling mode.

These imperfections are applicable to hinged systems with and without rotational spring stiffness’s. Sandwich panels which contain imperfections larger than the reasonable imperfections result in a significant stiffness loss to face sheets of either 0.8 or 1.5 or 3.0 mm. The given range of the imperfection envelope contain coupled instabilities as has been observed in section 4.5.6. While the sandwich panel bends due to the second order effect the compression stress in the most compressed face sheet increase. If the compression stress localization exceeds the stress wherefore wrinkling case I rigid base occurs fails the sandwich panel by exceeding strength of the core and/or face sheet.

### 4.5.8 Conclusion FE model

Second order effects are visible from a nonlinear bending stiffness behaviour in the force-out-of-plane diagram. A sudden drop of the bending stiffness is induced by face sheet wrinkling. Face sheet wrinkling is observed by a locally
decrease of the axial stiffness in the force-axial shortening diagram. If the axial stiffness response of the sandwich panel decreases face sheet wrinkling occurs. Whether wrinkling case I, case II or case III occurs depends to the magnitude of the out-of-plane deformations. To prevent these three wrinkling cases the compression load in the panel needs to be lower than the critical wrinkling load. Wrinkling of a single face sheet only occurs in structures subjected to bending or eccentric loaded sandwich panels.

To simulate the exact sandwich panel buckling behaviour initial imperfections need to be assigned to the Euler buckling mode. These imperfections need to be measured in future experimental research. A second approach of these imperfections is to assign the maximum allowable manufacturing alignment or the maximum allowable alignment according to the building codes to the FE-analysis.

According to assumed rotational spring stiffness sandwich panel failure is observed in the FE model:

- Failure of sandwich panels with 0,8 mm face sheets is initiated by wrinkling due to the increasing axial shortening and the constant rotations of the supports at an increasing compression load.
- Failure of sandwich panels with 1,5 or 3,0 mm face sheets is initiated by a second order effect which activates wrinkling case I rigid base due the increasing out-of-plane deformations. The sandwich panel bends and stress localizations occur wherefore wrinkling results in a significant stiffness loss of the sandwich panel.

In general, the following is concluded from the influence of geometrical imperfections:

- Imperfections of mode 1 (Euler buckling) have a significant effect to the bending stiffness behaviour compared to imperfections of mode 2 (wrinkling).
- Imperfections of mode 1 (Euler buckling) have relatively small influences to the axial stiffness behaviour with respect to imperfections of mode 2 (wrinkling).
- With an increase of face sheet thickness decreases the size of the envelope. Therefore, thin face sheets are more sensitive to imperfections of either mode 1 or mode 2.

Reasonable imperfections obtained from the GNIA are:

- $L/10000$ and $L/750$ to the Euler buckling mode;
- 1-30% of the face sheet thickness to the wrinkling mode.

Avoid hinge supports in an experimental buckling test. These supports conditions are hard to construct, but even harder to simulate in a FE model due to GNL contact interaction behaviour with static or dynamic friction. The numerical model is unable to simulate the buckling behaviour because of contact interaction behaviour in the supports. However, without the contact interaction behaviour the model predicts the buckling behaviour well.
5. **CONCLUSION**

Conclusions are given in the same order as the chapters are treated.

*Literature study*

- The linear sandwich panel theory is valid to sandwich panels in bending. This theory uses superposition of the core shear deformations and the face sheet bending deformations.
- The formula of Allen [8] distinguishes three types of wrinkling. The wrinkling formula neglects the contribution of the core shear modulus of elasticity and the complete length and width of the sandwich panel. Regardless of these missing properties, Allen’s theory performs well to estimate the wrinkling behaviour (local buckling).
- The discussed reciprocal value of the Euler buckling formula and the shear buckling perform well to estimate the global buckling behaviour.
- As a result of a second order effect, compression stress localizations occur in a single face sheet which cause face sheet wrinkling case I – rigid base. Interaction buckling results in a significant stiffness loss and an axial shortening of the whole panel.

*Material properties*

- A 95% confidence interval of the XPS and GFRP material proves the constancy of well-engineered materials with small variations.
- The material behaviour of the orthotropic GFRP face sheet material is linear elastic to thin face sheets of 0.8 and 1.5 mm and nonlinear elastic to face sheets of 3.0 mm.
- The ratio of the fibre to matrix content results in linear or nonlinear material behaviour.
- The material behaviour of the XPS core is nonlinear in compression, tension and shear.
- In tension the XPS has a longer linear elastic branch at lower stress levels than in compression.
- The tensile strength of the XPS is larger than the compression strength.

*Load introduction test*

- Enclosing the sandwich panel load edge over a height of at least 25 mm prevents premature crushing failure of the face sheets due to the applied load on the panel.
- Wrinkles develop along the edge of the sandwich panel.
- The geometric instability type wrinkling case I rigid base initiates failure of short sandwich panels independent of the face sheet thickness. Geometrical imperfections (skew specimen) cause an uneven load distribution over the sandwich panel wherefore wrinkling case I rigid base is observed.
- Failure occurs in either the face sheet or core material.
- Thin face sheets of 0.8 mm are more sensitive to wrinkling behaviour than thicker face sheets.

*Sandwich panel buckling test*

- Rotations of the supports remain (almost) equal but the axial shortening of the sandwich panel increases significantly to panels with 0.8 mm face sheets. This behaviour refers to wrinkling.
- Geometrical imperfections in panels with 0.8 mm face sheets are in the order of the face sheet thickness.
- Thin face sheets of 0.8 mm are sensitive to local geometrical face sheet imperfections caused during the manufacturing process of the panel. These imperfections initiate the geometric instability type wrinkling.
Thin face sheets of 0,8 mm are also more sensitive to wrinkling at lower load levels than thicker face sheets of 1,5 mm and 3,0 mm. Wrinkles develop along the sandwich panel edge. Due to the second order effect the out-of-plane deformations increase and a localization of compression stresses results in face sheet wrinkling case I rigid base. As a result of the second order effect wrinkling causes failure of the core or face sheet material. This behaviour is referred to coupled instabilities and occurs to face sheets of 1,5 and 3,0 mm. Coupled instabilities result in a significant global stiffness loss wherefore material failure occurs. Failure is observed in the core and face sheet material. Failure types are: Face sheet compressive failure, local delamination face sheet, core material tensile failure and core shear failure.

**FE-model short sandwich panels**

A numerical model has been developed to simulate GNL axial stiffness behaviour of sandwich panels with a length of 150 mm. From the FE-analysis is concluded:

- The estimation of the wrinkling wavelength according to the formula of Allen [8] performs well to thin face sheets of 0,8 mm but results in an overestimation of the wrinkling length at thicker face sheets.
- The two instability modes refer to wrinkling.
- Wrinkling case I, II or III is dependant to the face sheet thickness. Thin face sheets of 0,8 or 1,5 mm are sensitive to wrinkling case I. Face sheets of 3,0 mm are sensitive to wrinkling case II and III.
- The numerical model is able to estimate the axial stiffness by including geometrical imperfections of the first and second buckling mode wrinkling. Including geometrical imperfections of a skew geometry might improve the accurateness of the FE-analysis.
- Thin face sheets of 0,8 mm are more sensitive to wrinkling than thicker face sheets of 1,5 and 3,0 mm.
- Thick face sheets affect the axial stiffness behaviour more than thin face sheets.
- Linearization of boundary conditions in an eigenvalue analysis influence the buckling behaviour.
- The assumption of an equal modulus of elasticity in compression and tension of orthotropic GFRP face sheets is an overestimation. A reduction of 5-18% of the tensile modulus of elasticity results a reasonable assumption of the compression modulus of elasticity of orthotropic face sheets.

**FE-model large sandwich panels**

- The LBA performs well compared to the theoretical exact solution.
- The LBA and GNIA are able to estimate the buckling load and modes of panels with 0,8 mm face sheets.
- To simulate the exact buckling behaviour of the experimental tests of sandwich panels with 1,5 and 3,0 mm face sheets require a GNIA with contact interaction behaviour at the supports. The contact interaction is nonlinear behaviour which will be ignored in a LBA. All contact conditions will be fixed in a LBA. The LBA results in an overestimation of the buckling load. Because of the overestimation of the LBA imperfections needs to be assigned to the GNL analysis by a user defined load or displacement amplitude.
- In a hinged system the buckling mode one and two results in respectively Euler buckling and wrinkling.
- In a fully clamped system both buckling modes result in wrinkling.
- With respect to a hinged system with an arbitrary linear rotational spring stiffness the GNIA shows reasonable imperfection boundaries. These boundaries result in an envelope with a range of L/10000 to L/750 and 1-30% of the face sheet thickness to respectively the Euler buckling mode and wrinkling mode.
- Imperfections of the wrinkling mode affect the axial stiffness behaviour while imperfections of the Euler buckling mode affect the bending stiffness behaviour.
− Geometrical imperfections of gaps, glue agglomerations and a skew geometry are observed in the experimental tests. These imperfections might influence the buckling behaviour of the sandwich panel, but are excluded in the FE-analysis.
− The discussed analytical failure mechanisms to predict the individual geometrical instability loads perform well.

**Main conclusion**

The discussed wrinkling equations and the Euler buckling equation result in an analytical solution of the buckling load. Euler buckling results in the exact solution and wrinkling according to Allen results in a conservative solution. Both instability modes need to be determined to estimate the dominant buckling load. Wrinkling case I occurs in eccentric loaded structures or structures loaded in bending. Wrinkling case II and case III occur in axially loaded sandwich panels.

Analytical calculations of individual geometric instabilities are insufficient to determine the sandwich panel behaviour of coupled instabilities. A 2D in-plane geometrical nonlinear analysis which includes imperfections (GNIA) is required to simulate the buckling behaviour of a thin walled GFRP sandwich panels. Second order effects cannot be ignored. Due to second order effects bending deformations increase and a localization of compression stresses results in face sheet wrinkling case I rigid base. To simulate behaviour of coupled instabilities by a deformation controlled analysis in a FE-model, the following input parameters are observed to be required:

− Although the core and face sheet material behaviour are orthotropic, isotropic material behaviour is sufficient.
− The face sheet centre line needs to be constraint to the core edge.
− Minimum required material properties are obtained from experimental tests:
  ▪ Face sheet compression modulus of elasticity ($E$);
  ▪ Face sheet Poisson ratio ($v$);
  ▪ Core modulus of elasticity ($E$);
  ▪ Core Poisson ratio ($v$).
− The examined boundary conditions in the experimental tests are unable to simulate in the FE model due to linearization and ignoring of inelastic behaviour by a linear buckling analysis. Boundary conditions are applied to an infinite stiff element attached to both ends of the panel.
− Plane stress elements core and Euler-Bernoulli elements face sheet;
− The wrinkling wave lengths observed in experimental tests are smaller or equal to the minimum wrinkling wave length of the analytical equation. The analytical equation is sufficient to 0,8 mm face sheets but results in an overestimation to face sheets of 1,5 and 3,0 mm. The mesh size must be able to simulate the minimum wrinkling wave length according to the experimental tests.

With respect to the performed experimental buckling tests on sandwich panels the FE-model is unable to estimate the exact buckling behaviour. The assumed hinge connection in the sandwich panel tests performed as a rotational spring stiffness. A simulation of the rotational spring stiffness with a GNL contact interaction analysis is considered to be out of scope. To conclude these observations a hinge support in a sandwich panel buckling test can better be avoided. Support conditions of the experimental test setup needs to be examined to prevent a GNL contact interaction analysis in a FE model.

Regardless of these boundary conditions individual buckling loads can be predicted by an eigenvalue analysis and checked to the analytical solution. Buckling modes of the eigenvalue analysis represent the geometrical
imperfections assigned to a GNL analysis. The GNIA will give an appropriate prediction of the buckling behaviour. Reasonable geometrical imperfections with respect to Euler buckling and wrinkling are respectively in the range of $L/10000$ to $L/750$ and 1-30% of the face sheet thickness.
6. RECOMMENDATIONS AND FUTURE WORK

The stability behaviour of axially loaded sandwich panels is discussed. A brief overview of recommendations and future work of this topic will be given.

6.1 RECOMMENDATIONS

Experimental tests

Material tests conclude small deviations within material properties. To improve test results of two test methods, recommendations will be given to:

- Transverse strain measurement face sheet.
- Compression modulus of elasticity face sheet.
- Lateral support of the specimen in core shear test.

The transverse strain measurement of GFRP can better be performed with a video extensometer (non-contact measurement) than a strain gauge of 6,0 mm. A bundle of fibres in either the transverse or longitudinal fibre direction has a width of 3,0 mm. The strain measurement over 6,0 mm is too small and gives unreliable strain measurements. Results of a video extensometer are more accurate and can be derived from arbitrary gauge lengths after the test. The location of the measurement is adjustable to gather appropriate results.

The same measurement technique of the video extensometer can be used to measure the compression modulus of elasticity of the GFRP.

Two roller supports are added to the XPS shear test to prevent a bending moment in the XPS specimen due to eccentric loading. Without these supports the calculated shear stress results in a combination of shear and tensile stresses.

Irregularities in the sandwich panel geometry needs to be avoided in the manufacturing process:

- Circular indentations in thin face sheets.
- Gaps between two adjacent XPS core material plates. To improve the shear stiffness of the panel the edges of the plates need to be attached by an adhesive.
- Glue agglomerations between the face sheet and core, especially to prevent geometrical imperfections in sandwich panels with face sheets of 0,8 mm.

Sandwich panel buckling test

- Avoid hinge supports in experimental buckling tests.
- Prevent contact interaction behaviour in the supports at both ends of the panel.
- Geometrical imperfections need to be measured prior to the test is performed.

General recommendations are:

- To prevent interaction buckling in eccentric loaded structures or in structures loaded in bending the face sheet compression stress needs to be lower than the stresses of wrinkling case I – rigid base.
- The use of GFRP sandwich panels in load bearing structures is recommended with thicker face sheets than 3,0 mm to prevent wrinkling or coupled instabilities.
6.2 FUTURE WORK

− The fibre reinforced composite tensile test described by the test Standard contain a transverse strain measurement. This measurement can be performed with strain gauges. The strain gauge length is restricted by the width of the specimen but also to the fibre bundles which represent a woven fabric. A bundle of fibres in either the transverse or longitudinal direction has a width of 3,0 mm. The location of the strain gauge is important but also the gauge length. Whether this gauge length has to measure the strain over two or more fibre bundles is excluded in the test Standard. The gauge length of a transverse strain measurement needs to be examined.

− Before the experimental buckling test will be performed the support conditions need to be investigated. A predefined rotational spring stiffness in the connection between the support and sandwich panel end is recommended. Assumptions of the connection stiffness need to be validated by experimental tests and verified by a FE model.

− Another interesting investigation about the supports is the height wherefore sandwich panel ends are enclosed to prevent premature crushing failure of the face sheet or premature wrinkling failure. To insert the load into the sandwich panel end different load configurations need to be examined. This could be done by different sandwich panel geometries or experimental test setups.

− An analytical equation to the coupled instabilities of a sandwich panel validated by experimental tests is interesting to investigate. The instabilities Euler buckling and wrinkling are often examined individually, but a combination of these modes are seldom, especially in experimental test results. A simplified analytical equation which contain the transition between these modes should be investigated and validated by experimental test results.
7. APPENDICES

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STABILITY OF AXially LOADED GFRP SANDWICH WALL PANELS

APPENDICES

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5 February 2016
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<td>37</td>
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<tr>
<td>Appendix L</td>
<td>Imperfection sensitivity analysis large sandwich panels</td>
<td>41</td>
</tr>
<tr>
<td>Appendix M</td>
<td>Python scripts</td>
<td>49</td>
</tr>
</tbody>
</table>
APPENDIX A  TEST TYPE 1: GFRP TENSILE PROPERTIES

Table 1 to Table 4 show test results of the GFRP tensile test on specimens with a thickness of 0.8 mm. Table 5 to Table 8 show test results of the GFRP tensile test on specimens with a thickness of 1.5 mm. Table 9 to Table 12 show test results of the GFRP tensile test on specimens with a thickness of 3.0 mm.

According to the test standard [2] the region of the longitudinal strain of $\varepsilon' = 0.003$ to $\varepsilon'' = 0.015$ is valid to derive the poison ratio by using the ratio of the transverse strain over the longitudinal strain. However, the transverse strain results of specimen 27, 28, 08, and 09 are inaccurate over the strain region corresponding to a longitudinal strain region of $\varepsilon' = 0.003$ to $\varepsilon'' = 0.015$. By trial and error the region of the longitudinal strain of $\varepsilon' = 0$ to $\varepsilon'' = 0.007$ leads to a correlation coefficient ($R^2$-value) of at least 0.99 for specimen 27, 28, 08, and 09, determining the poison ratio.
0,8 mm face sheet thickness

Table 1: Test results 41 and 42

<table>
<thead>
<tr>
<th></th>
<th>GFRP-0,8mm-41</th>
<th>Tensile E-modulus</th>
<th>GFRP-0,8mm-42</th>
<th>Tensile E-modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure (σ_u)</td>
<td>129</td>
<td>[ MPa ]</td>
<td>146</td>
<td>[ MPa ]</td>
</tr>
<tr>
<td>Strain at failure (ε_u)</td>
<td>1,647</td>
<td>[ % ]</td>
<td>1,844</td>
<td>[ % ]</td>
</tr>
<tr>
<td>Modulus of elasticity (E)</td>
<td>9621</td>
<td>[ MPa ]</td>
<td>10150</td>
<td>[ MPa ]</td>
</tr>
</tbody>
</table>

Table 2: Test results 43 and 44

<table>
<thead>
<tr>
<th></th>
<th>GFRP-0,8mm-43</th>
<th>Tensile E-modulus</th>
<th>GFRP-0,8mm-44</th>
<th>Tensile E-modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure (σ_u)</td>
<td>157</td>
<td>[ MPa ]</td>
<td>145</td>
<td>[ MPa ]</td>
</tr>
<tr>
<td>Strain at failure (ε_u)</td>
<td>1,945</td>
<td>[ % ]</td>
<td>1,783</td>
<td>[ % ]</td>
</tr>
<tr>
<td>Modulus of elasticity (E)</td>
<td>10048</td>
<td>[ MPa ]</td>
<td>9680</td>
<td>[ MPa ]</td>
</tr>
</tbody>
</table>
0.8 mm face sheet thickness

Table 3: Test results 45 and 46

<table>
<thead>
<tr>
<th></th>
<th>GFRP-0,8mm-45</th>
<th>Tensile E-modulus</th>
<th>GFRP-0,8mm-46</th>
<th>Tensile E-modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$)</td>
<td>148 [MPa]</td>
<td>148 [MPa]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>1,795 [%]</td>
<td>1,836 [%]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus of elasticity ($E$)</td>
<td>10240 [MPa]</td>
<td>10200 [MPa]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Left test results 47 and right test results 48 of 0.8 mm GFRP.

<table>
<thead>
<tr>
<th></th>
<th>GFRP-0,8mm-45</th>
<th>Tensile E-modulus</th>
<th>GFRP-0,8mm-46</th>
<th>Tensile E-modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$)</td>
<td>144 [MPa]</td>
<td>133 [MPa]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>1,810 [%]</td>
<td>1,753 [%]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus of elasticity ($E$)</td>
<td>9702 [MPa]</td>
<td>9831 [MPa]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poison ratio</td>
<td>0.35 [-]</td>
<td>0.39 [-]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1.5 mm face sheet thickness

Table 5: Test results 21 and 22

<table>
<thead>
<tr>
<th></th>
<th>Test results 21</th>
<th>Test results 22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$)</td>
<td>104 [MPa]</td>
<td>91 [MPa]</td>
</tr>
<tr>
<td>Strain at failure ($\epsilon_u$)</td>
<td>1,590 [%]</td>
<td>1,484 [%]</td>
</tr>
<tr>
<td>Modulus of elasticity ($E$)</td>
<td>7669 [MPa]</td>
<td>7363 [MPa]</td>
</tr>
</tbody>
</table>

Table 6: Test results 23 and 24

<table>
<thead>
<tr>
<th></th>
<th>Test results 23</th>
<th>Test results 24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$)</td>
<td>85 [MPa]</td>
<td>97 [MPa]</td>
</tr>
<tr>
<td>Strain at failure ($\epsilon_u$)</td>
<td>1,434 [%]</td>
<td>1,473 [%]</td>
</tr>
<tr>
<td>Modulus of elasticity ($E$)</td>
<td>6957 [MPa]</td>
<td>7629 [MPa]</td>
</tr>
</tbody>
</table>
1.5 mm face sheet thickness

Table 7: Test results 25 and 26

<table>
<thead>
<tr>
<th></th>
<th>Test results 25</th>
<th>Test results 26</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$)</td>
<td>83 [MPa]</td>
<td>82 [MPa]</td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>1,346 [%]</td>
<td>1,396 [%]</td>
</tr>
<tr>
<td>Modulus of elasticity ($E$)</td>
<td>6930 [MPa]</td>
<td>7036 [MPa]</td>
</tr>
</tbody>
</table>

Table 8: Left test results 27 and right test results 28 of 1.5 mm GFRP.

<table>
<thead>
<tr>
<th></th>
<th>Left test results 27</th>
<th>Right test results 28</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$)</td>
<td>86 [MPa]</td>
<td>80 [MPa]</td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>1,387 [%]</td>
<td>1,280 [%]</td>
</tr>
<tr>
<td>Modulus of elasticity ($E$)</td>
<td>7154 [MPa]</td>
<td>7053 [MPa]</td>
</tr>
<tr>
<td>Poison ratio</td>
<td>0.11 [-]</td>
<td>0.08 [-]</td>
</tr>
</tbody>
</table>
3,0 mm face sheet thickness

Table 9: Test results 02 and 03

<table>
<thead>
<tr>
<th></th>
<th>GFRP-3mm-02</th>
<th>Tensile E-modulus</th>
<th>GFRP-3mm-03</th>
<th>Tensile E-modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$)</td>
<td>55 [MPa]</td>
<td>56 [MPa]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>0,996 [%]</td>
<td>1,221 [%]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus of elasticity ($E$)</td>
<td>6514 [MPa]</td>
<td>6056 [MPa]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 10: Test results 04 and 05

<table>
<thead>
<tr>
<th></th>
<th>GFRP-3mm-04</th>
<th>Tensile E-modulus</th>
<th>GFRP-3mm-05</th>
<th>Tensile E-modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$)</td>
<td>61 [MPa]</td>
<td>63 [MPa]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>1,286 [%]</td>
<td>1,176 [%]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus of elasticity ($E$)</td>
<td>6214 [MPa]</td>
<td>7099 [MPa]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.0 mm face sheet thickness

Table 11: Test results 06 and 07

<table>
<thead>
<tr>
<th></th>
<th>06</th>
<th>07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$) [MPa]</td>
<td>60</td>
<td>58</td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$) [%]</td>
<td>1,175</td>
<td>1,172</td>
</tr>
<tr>
<td>Modulus of elasticity ($E$) [MPa]</td>
<td>7020</td>
<td>6618</td>
</tr>
</tbody>
</table>

Table 12: Left test results 08 and right test results 09 of 3.0 mm GFRP.

<table>
<thead>
<tr>
<th></th>
<th>08</th>
<th>09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$) [MPa]</td>
<td>66</td>
<td>64</td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$) [%]</td>
<td>1,186</td>
<td>1,460</td>
</tr>
<tr>
<td>Modulus of elasticity ($E$) [MPa]</td>
<td>7171</td>
<td>6710</td>
</tr>
<tr>
<td>Poison ratio</td>
<td>0.26</td>
<td>0.27</td>
</tr>
</tbody>
</table>
APPENDIX B TEST TYPE 2: XPS SHEAR PROPERTIES

A dashed red line marks the slope of the force-deformation diagram over a region between 10 to 40 percent of the maximum average force. This region represents the linear branch in the force-deformation diagram with a correlation coefficient of at least 0.99 (R²-value) to derive the shear modulus of elasticity of the XPS.
Table 13: Test results G01. Failure occurs by exceeding the shear strength of the XPS at the bottom of the specimen.

<table>
<thead>
<tr>
<th></th>
<th>LVDT 06</th>
<th>LVDT 07</th>
<th>Average</th>
<th>10 to 40 % of Fmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force [kN]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deformation [mm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Test speed increases from 0,5 to 1,0 mm/min

Test speed increases from 1,0 to 1,5 mm/min

R² = 0,999

| Shear strength (τ₀) | 0,490 [MPa] |
| Shear modulus (G)    | 10,250 [MPa] |

Table 14: Test results G02. Failure occurs by exceeding the shear strength of the XPS at the middle of the specimen.

<table>
<thead>
<tr>
<th></th>
<th>LVDT 06</th>
<th>LVDT 07</th>
<th>Average</th>
<th>10 to 40 % of Fmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force [kN]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deformation [mm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Test speed increases from 0,5 to 1,0 mm/min

Test speed increases from 1,0 to 1,5 mm/min

R² = 0,999

| Shear strength (τ₀) | 0,513 [MPa] |
| Shear modulus (G)    | 10,971 [MPa] |
Table 15: Test results G03. Failure occurs by exceeding the shear strength of the XPS at the top of the specimen.

<table>
<thead>
<tr>
<th>Shear strength (τ_u)</th>
<th>0,474 [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear modulus (G)</td>
<td>10,144 [MPa]</td>
</tr>
</tbody>
</table>

Table 16: Test results G04. Failure occurs by exceeding the shear strength of the XPS at the top of the specimen.

<table>
<thead>
<tr>
<th>Shear strength (τ_u)</th>
<th>0,489 [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear modulus (G)</td>
<td>9,590 [MPa]</td>
</tr>
</tbody>
</table>
Table 17: Test results G05. Failure occurs by exceeding the shear strength of the XPS at the top of the specimen.

<table>
<thead>
<tr>
<th>Shear strength ($\tau_u$)</th>
<th>0.477 [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear modulus ($G$)</td>
<td>10.692 [MPa]</td>
</tr>
</tbody>
</table>
ball joint

jack force with load cell

steel block 31 x 50 x 100 mm attached with three M12 bolts to steel plate

front steel plate

steel plate 15 x 50 x 590 mm glued to 3 mm GRP

Sandwich panel 31 x 50 x 470 mm:
- 3 mm GRP
- 25 mm XPS
- 3 mm GRP

vertical roller support

device holder G

steel plate 15 x 50 x 590 mm glued to 3 mm GRP

back steel plate

steel block 33 x 50 x 100 mm attached with three M12 bolts to steel plate

testing machine

ball joint
APPENDIX C    TEST TYPE 3: XPS COMRESSIVE PROPERTIES
Table 18: Left test results E4-00 and right test results E4-01

<table>
<thead>
<tr>
<th></th>
<th>Left Test Results</th>
<th>Right Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$)</td>
<td>0,389 [MPa]</td>
<td>0,367 [MPa]</td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>1,816 [%]</td>
<td>2,165 [%]</td>
</tr>
<tr>
<td>Initial modulus of elasticity ($E$)</td>
<td>40,1 [MPa]</td>
<td>26,5 [MPa]</td>
</tr>
</tbody>
</table>

Table 19: Left test results E4-02 and right test results E4-03

<table>
<thead>
<tr>
<th></th>
<th>Left Test Results</th>
<th>Right Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$)</td>
<td>0,383 [MPa]</td>
<td>0,409 [MPa]</td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>2,435 [%]</td>
<td>2,551 [%]</td>
</tr>
<tr>
<td>Initial modulus of elasticity ($E$)</td>
<td>28,5 [MPa]</td>
<td>32,8 [MPa]</td>
</tr>
</tbody>
</table>
Table 20: Left test results E4-04 and right test results E4-05

| Stress at failure ($\sigma_u$) | 0.416 | 0.397 | [MPa] |
| Strain at failure ($\varepsilon_u$) | 2.624 | 2.402 | [%] |
| Initial modulus of elasticity ($E$) | 28.4 | 30.8 | [MPa] |

Table 21: Left test results E4-06 and right test results E4-07

| Stress at failure ($\sigma_u$) | 0.399 | 0.427 | [MPa] |
| Strain at failure ($\varepsilon_u$) | 2.287 | 2.536 | [%] |
| Initial modulus of elasticity ($E$) | 30.5 | 30.4 | [MPa] |
Table 22: Left test results E4-08 and right test results E4-09

<table>
<thead>
<tr>
<th></th>
<th>Stress at failure ($\sigma_u$)</th>
<th>Strain at failure ($\varepsilon_u$)</th>
<th>Initial modulus of elasticity ($E$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0,414 (MPa)</td>
<td>2,672 (%)</td>
<td>29,5 (MPa)</td>
</tr>
</tbody>
</table>

Compressional E-modulus, $R^2 = 0,998$

Table 23: Left test results E4-10 and right test results E4-11

<table>
<thead>
<tr>
<th></th>
<th>Stress at failure ($\sigma_u$)</th>
<th>Strain at failure ($\varepsilon_u$)</th>
<th>Initial modulus of elasticity ($E$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0,402 (MPa)</td>
<td>2,895 (%)</td>
<td>25,6 (MPa)</td>
</tr>
</tbody>
</table>

Compressional E-modulus, $R^2 = 0,998$
APPENDIX D

TEST TYPE 4: XPS TENSILE PROPERTIES
Table 24: Left test results E5-00 and right test results E5-01

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left Test Results</th>
<th>Right Test Results</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$)</td>
<td>0.714</td>
<td>0.723</td>
<td>MPa</td>
</tr>
<tr>
<td>Strain at failure ($\epsilon_u$)</td>
<td>4.739</td>
<td>4.904</td>
<td>%</td>
</tr>
<tr>
<td>Modulus of elasticity ($E$)</td>
<td>33.9</td>
<td>34.1</td>
<td>MPa</td>
</tr>
</tbody>
</table>

Table 25: Left test results E5-02 and right test results E5-03

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left Test Results</th>
<th>Right Test Results</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$)</td>
<td>0.723</td>
<td>0.715</td>
<td>MPa</td>
</tr>
<tr>
<td>Strain at failure ($\epsilon_u$)</td>
<td>4.612</td>
<td>4.696</td>
<td>%</td>
</tr>
<tr>
<td>Modulus of elasticity ($E$)</td>
<td>33.9</td>
<td>34.1</td>
<td>MPa</td>
</tr>
</tbody>
</table>
Table 26: Left test results E5-04 and right test results E5-05

<table>
<thead>
<tr>
<th></th>
<th>E5-04</th>
<th>E5-05</th>
<th>[ MPa ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$)</td>
<td>0.715</td>
<td>0.706</td>
<td></td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>4,042</td>
<td>4,570</td>
<td>[ % ]</td>
</tr>
<tr>
<td>Modulus of elasticity ($E$)</td>
<td>34.1</td>
<td>33.2</td>
<td>[ MPa ]</td>
</tr>
</tbody>
</table>

Tensile E-modulus, $R^2 = 0.999$

Table 27: Test results E5-06

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th>[ MPa ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress at failure ($\sigma_u$)</td>
<td>0.727</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>4,866</td>
<td></td>
<td>[ % ]</td>
</tr>
<tr>
<td>Modulus of elasticity ($E$)</td>
<td>33.9</td>
<td></td>
<td>[ MPa ]</td>
</tr>
</tbody>
</table>

Tensile E-modulus, $R^2 = 0.999$
Legend:

- Jack with load cell
- Jack force F
- Symmetric dot-bone shaped specimen
- Steel blocks
- Testing machine clamps the steel blocks
- Steel blocks of 80 x 120 mm. The weight is shaped
- XPS clipped between 2 steel blocks
- Welded shear flaps on the blocks
- Welded shear flaps of the blocks 80 x 120 mm. The
- Welded shear flaps of the blocks
- Welded shear flaps of the blocks
- Welded shear flaps of the blocks
- Welded shear flaps of the blocks
APPENDIX E  TEST TYPE 5: LOAD INTRODUCTION CUBIC SANDWICH PANEL
0.8 mm face sheet

Table 28: Left test results S4-40 and right the front view of the specimen with location measure equipment.

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure load ($F_u$)</td>
<td>21.1</td>
<td>[kN]</td>
</tr>
<tr>
<td>Axial shortening ($\delta_u$)</td>
<td>2.3</td>
<td>[mm]</td>
</tr>
<tr>
<td>Maximum lateral deformation</td>
<td>-0.35</td>
<td>[mm]</td>
</tr>
</tbody>
</table>

Table 29: Left test results S4-41 and right test results S4-42

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure load ($F_u$)</td>
<td>18.0</td>
<td>17.1</td>
</tr>
<tr>
<td>Axial shortening ($\delta_u$)</td>
<td>1.14</td>
<td>1.38</td>
</tr>
<tr>
<td>Maximum lateral deformation</td>
<td>-0.16</td>
<td>-0.13</td>
</tr>
</tbody>
</table>
0.8 mm face sheet

Table 30: Test results S4-43.

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure load ($F_u$)</td>
<td>19.8 kN</td>
</tr>
<tr>
<td>Axial shortening ($\delta_u$)</td>
<td>1.18 mm</td>
</tr>
<tr>
<td>Maximum lateral deformation</td>
<td>-0.11 mm</td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>0.70 %</td>
</tr>
</tbody>
</table>

Table 31: Test results S4-44

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure load ($F_u$)</td>
<td>25.3 kN</td>
</tr>
<tr>
<td>Axial shortening ($\delta_u$)</td>
<td>1.54 mm</td>
</tr>
<tr>
<td>Maximum lateral deformation</td>
<td>-0.18 mm</td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>0.89 %</td>
</tr>
</tbody>
</table>
1.5 mm face sheet

Table 32: Left test results S4-20 and right test results S4-21

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure load ($F_u$)</td>
<td>45,9</td>
<td>50</td>
<td>43,0</td>
<td>102,0</td>
<td>2,18</td>
<td>-0,27</td>
</tr>
<tr>
<td>Stress at failure</td>
<td>43,0</td>
<td>50</td>
<td>95,5</td>
<td>102,0</td>
<td>2,22</td>
<td>-0,23</td>
</tr>
<tr>
<td>Axial shortening ($\delta_u$)</td>
<td>2,18</td>
<td>50</td>
<td>-0,27</td>
<td>2,22</td>
<td>-0,23</td>
<td>-0,27</td>
</tr>
<tr>
<td>Maximum lateral deformation</td>
<td>-0,27</td>
<td>50</td>
<td>-0,23</td>
<td>-0,23</td>
<td>-0,27</td>
<td>-0,23</td>
</tr>
</tbody>
</table>

Table 33: Test results S4-22. The structure stiffens after the first wrinkle and fails due to a second wrinkle in the opposite face sheet.

<table>
<thead>
<tr>
<th></th>
<th>Force [kN]</th>
<th>Deformation [mm]</th>
<th>Axial shortening</th>
<th>Strain face sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure load ($F_u$)</td>
<td>32,7</td>
<td>50</td>
<td>1,97</td>
<td>0,79</td>
</tr>
<tr>
<td>Axial shortening ($\delta_u$)</td>
<td>1,97</td>
<td>50</td>
<td>0,79</td>
<td>1,97</td>
</tr>
<tr>
<td>Maximum lateral deformation</td>
<td>-0,39</td>
<td>50</td>
<td>1,97</td>
<td>-0,39</td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>0,79</td>
<td>50</td>
<td>1,97</td>
<td>0,79</td>
</tr>
</tbody>
</table>
1.5 mm face sheet

Table 34: Test results S4-23

<table>
<thead>
<tr>
<th></th>
<th>Failure load ( F_u )</th>
<th>Axial shortening ( \delta_u )</th>
<th>Maximum lateral deformation</th>
<th>Strain at failure ( \varepsilon_u )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>41.0 ( [kN] )</td>
<td>2.00 ( [mm] )</td>
<td>-0.27 ( [mm] )</td>
<td>1.12 ( [%] )</td>
</tr>
</tbody>
</table>

![Graphs showing Axial shortening, Strain face sheet, and Force vs. Deformation](image-url)
3.0 mm face sheet

Table 35: Left test results S4-07 and right test results S4-08

<table>
<thead>
<tr>
<th></th>
<th>Left Test (S4-07)</th>
<th>Right Test (S4-08)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure load ($F_u$)</td>
<td>86.8 [kN]</td>
<td>78.8 [kN]</td>
</tr>
<tr>
<td>Stress at failure</td>
<td>96.4 [MPa]</td>
<td>87.5 [MPa]</td>
</tr>
<tr>
<td>Axial shortening ($\delta_u$)</td>
<td>2.45 [mm]</td>
<td>2.51 [mm]</td>
</tr>
<tr>
<td>Maximum lateral deformation</td>
<td>-0.34 [mm]</td>
<td>-0.39 [mm]</td>
</tr>
</tbody>
</table>

Table 36: Left test results S4-09 and right test results S4-10

<table>
<thead>
<tr>
<th></th>
<th>Left Test (S4-09)</th>
<th>Right Test (S4-10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure load ($F_u$)</td>
<td>78.4 [kN]</td>
<td>83.8 [kN]</td>
</tr>
<tr>
<td>Stress at failure</td>
<td>87.1 [MPa]</td>
<td>93.1 [MPa]</td>
</tr>
<tr>
<td>Axial shortening ($\delta_u$)</td>
<td>2.21 [mm]</td>
<td>2.35 [mm]</td>
</tr>
<tr>
<td>Maximum lateral deformation</td>
<td>-0.40 [mm]</td>
<td>-0.24 [mm]</td>
</tr>
</tbody>
</table>
3.0 mm face sheet

Table 37: Test results S4-05

<table>
<thead>
<tr>
<th></th>
<th>Axial shortening</th>
<th>Strain face sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure load ($F_u$)</td>
<td>96.1 kN</td>
<td>-</td>
</tr>
<tr>
<td>Axial shortening ($\delta_u$)</td>
<td>2.74 mm</td>
<td>-</td>
</tr>
<tr>
<td>Maximum lateral deformation</td>
<td>-0.30 mm</td>
<td>-</td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>1.60 %</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 38: Test results S4-06

<table>
<thead>
<tr>
<th></th>
<th>Axial shortening</th>
<th>Strain face sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure load ($F_u$)</td>
<td>75.3 kN</td>
<td>-</td>
</tr>
<tr>
<td>Axial shortening ($\delta_u$)</td>
<td>2.30 mm</td>
<td>-</td>
</tr>
<tr>
<td>Maximum lateral deformation</td>
<td>-0.24 mm</td>
<td>-</td>
</tr>
<tr>
<td>Strain at failure ($\varepsilon_u$)</td>
<td>1.39 %</td>
<td>-</td>
</tr>
</tbody>
</table>
APPENDIX F

TEST TYPE 6: TEST SETUP
APPENDIX G  TEST TYPE 6: FAILURE MECHANISMS
**Specimen S6-00**

Figure 1 shows wrinkling failure and the number given in figure 1 refers to the crack of figure 2. Figure 3 represents the front side of the specimen.

Figure 1: Left: Wrinkling failure at the back-side of the specimen. Right: Side view of the specimen.

Figure 2: Top left: The core material exceeded the tensile strength (back-side face sheet). Top right: As well as the core material as the glue exceeded the tensile strength (back-side face sheet). Bottom left: Wrinkling failure occurred at the gap between two core material plates (front-side face sheet). Bottom right: The core material exceeded the tensile strength and breaks (back-side face sheet).
Figure 3: Top left: Wrinkling failure at the front-side of the specimen. Top right: Side view specimen. Bottom left: The back-side face sheet is pressed into the core material caused by wrinkling failure. Bottom right: Wrinkling failure at the gap between two core material plates.

**Specimen S6-01**

The glue bond that connects the face sheet with the core material misses at the top of specimen S6-01 over an area of 100x900 mm² (height x width). The core material contains glue lines spread over the core material surface (Figure 4). The glue bonds to the core material but was unable to bond to the core material due to a bad adherence in the manufacturing process.

Figure 4: Missing adherence between the face sheet and core material.
Specimen S6-02

Failure modes of specimen S6-02 in figure 5 and figure 6.

Figure 5: Top: Wrinkling failure over the front face sheet of the specimen. 1: Wrinkle. 2: Wrinkling failure face sheet.

Figure 6: Top: Wrinkling failure over the back face sheet of the specimen. Bottom 1: wrinkling and core shear failure. Bottom middle: Compressive failure face sheet at force introduction. Bottom 3: Wrinkling/compressive failure face sheet.
Specimen S6-04

Three numbers in the figure below describe wrinkling. As well as delamination of the face sheet material as exceeding the tensile stress of the thickness direction of the core material occurred in the specimen (Figure 7 number 1). While number 2 and 3 of figure 7 show a face sheet deformation out-of-plane, number 3 shows a face sheet deformation in-plane. The out-of-plane and in-plane deformation differs over the width of the specimen.

Figure 7: Wrinkling failure.
STABILITY OF AXIALLY LOADED GFRP SANDWICH WALL PANELS

Specimen S6-05

Figure 8 (photo 1 and 4) shows the initial state of the specimen with geometrical imperfections of type A (gaps between the XPS plates). During the test small wrinkles develop along the longitudinal edge of the front face sheet (photo 2 and 3). The geometrical imperfection initiates to the failure mechanism wrinkling just above the gap between two XPS plates of photo 5 and 6 (Figure 8).

Figure 8: 1 and 4 show a gap between two XPS plates, 2 and 4 show local failure, and finally 5 and 6 represent wrinkling failure at the same location.
APPENDIX H  ROTATIONAL SPRING STIFFNESS
Linear rotational spring stiffness large sandwich panels (L = 2650 mm)

**Input data**

<table>
<thead>
<tr>
<th>Friction coefficient steel to steel ($\mu$)*</th>
<th>[ - ]</th>
<th>0,2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius steel rod (r)</td>
<td>[ mm ]</td>
<td>25</td>
</tr>
</tbody>
</table>

*$ = assumption$

$Kr = 0$  
Buckling length $L_{cr} = L$, Euler buckling (mode 1)

$Kr = \infty$  
Buckling length $L_{cr} = L/2$, Wrinkling (mode 2)

**Problem description**

At an arbitrary rotational spring stiffness the FEM model performs an eigenvalue analysis to compute the buckling load.

**Input: Data experimental tests**

<table>
<thead>
<tr>
<th>Specimens</th>
<th>S6-00</th>
<th>S6-02</th>
<th>S6-03</th>
<th>S6-04</th>
<th>S6-05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face sheet thickness $t_f$</td>
<td>[ mm ]</td>
<td>3,0</td>
<td>3,0</td>
<td>1,5</td>
<td>0,8</td>
</tr>
<tr>
<td>Failure load $F_y$</td>
<td>[ kN ]</td>
<td>374</td>
<td>333</td>
<td>134</td>
<td>87</td>
</tr>
<tr>
<td>Max. rotation at failure $\varphi$</td>
<td>[ Rad ]</td>
<td>0,004746</td>
<td>0,007412</td>
<td>0,010859</td>
<td>0,002238</td>
</tr>
</tbody>
</table>

*Rotational spring stiffness with $\mu = 0,2$*

Friction force $F_w = F_y \times \mu$  | [ N ] | 74820 | 66660 | 26700 | 17320 | 15100 |
Friction moment $M = F_w \times r$  | [ Nmm ] | 1,87E+06 | 1,67E+06 | 6,68E+05 | 4,33E+05 | 3,78E+05 |
Rotational spring stiffness $Kr$  | [ Nmm/Rad ] | 3,94E+08 | 2,25E+08 | 6,15E+07 | 1,94E+08 | 5,25E+07 |

*Rotational spring stiffness with $\mu = 0,5$*

Friction force $F_w = F_y \times \mu$  | [ N ] | 187050 | 166650 | 66750 | 43300 | 37750 |
Friction moment $M = F_w \times r$  | [ Nmm ] | 4,68E+06 | 4,17E+06 | 1,67E+06 | 1,08E+06 | 9,44E+05 |
Rotational spring stiffness $Kr$  | [ Nmm/Rad ] | 9,85E+08 | 5,62E+08 | 1,54E+08 | 4,84E+08 | 1,31E+08 |
Note that, the sandwich panel with a face sheet thickness of 0.8 mm fails at a load lower than the buckling load corresponding to a rotational spring stiffness of $Kr = 0$. Therefore the rotational spring stiffness of 0.8 mm face sheet thicknesses is zero.

By comparing the failure load of the experimental tests to the failure load at a rotational spring stiffness of zero can be concluded that the assumption of a hinge connection in the experimental tests was a conservative approximation of the exact behaviour. To sandwich panels with a face sheet thickness of 1.5 mm or 3.0 mm the friction coefficient of 0.2 is assumed to result in a valid approximation of the rotational spring stiffness. The thicker the face sheet the larger the rotational spring stiffness.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>S6-00</th>
<th>S6-02</th>
<th>S6-03</th>
<th>S6-04</th>
<th>S6-05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face sheet thickness $tf$ [mm]</td>
<td>3.0</td>
<td>3.0</td>
<td>1.5</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Rotational spring stiffness $Kr$ [Nmm/Rad]</td>
<td>$3.94E+08$</td>
<td>$2.25E+08$</td>
<td>$6.15E+07$</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
APPENDIX I  MESH SIZE SENSITIVITY ANALYSIS
Figure 1 represents the geometry of the model used in the mesh size sensitivity analysis with a rotational spring stiffness of zero. The analysis contains a mesh study to CPS4 and CPS8 core elements and B23 face sheet elements according to the order:

- Core width, $L = 150$ mm
- Core width, $L = 2650$ mm
- Core height, $L = 150$ mm
- Core height, $L = 2650$ mm
- Face sheet, $L = 150$ mm
- Face sheet, $L = 2650$ mm

**Constraint:** Surfaces: Master (M) and Slave (S)
A.) Tie $M = \text{Core, } S = \text{Face sheet}$
B.) Coupling $M = \text{Analytical rigid, } S(\text{nodes}) = \text{Core + Face sheet}$

![Figure 1: Top left: Geometry short panel. Top right: Geometry large panel. Bottom: Mesh distribution core and face sheet.](image-url)
**Core mesh width sensitivity analysis - System length 150 mm - CPS4**

<table>
<thead>
<tr>
<th>System length [mm]</th>
<th>150</th>
</tr>
</thead>
</table>

| B23 mesh size (msf) [mm] | 1 |

### 0,8 mm - CPS4

<table>
<thead>
<tr>
<th>Mesh height (mscy) [mm]</th>
<th>15</th>
<th>7,5</th>
<th>5</th>
<th>1,5</th>
<th>0,15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements height [-]</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Elements over width:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 [N]</td>
<td>916,4</td>
<td>699,2</td>
<td>661,7</td>
<td>358,3</td>
<td>354,4</td>
</tr>
<tr>
<td>10 [N]</td>
<td>887,7</td>
<td>664,0</td>
<td>626,5</td>
<td>302,5</td>
<td>298,8</td>
</tr>
<tr>
<td>30 [N]</td>
<td>871,0</td>
<td>642,5</td>
<td>605,1</td>
<td>264,1</td>
<td>260,7</td>
</tr>
<tr>
<td>50 [N]</td>
<td>869,6</td>
<td>640,6</td>
<td>603,2</td>
<td>260,2</td>
<td>256,7</td>
</tr>
</tbody>
</table>

**0,8 mm face sheet mesh study**

![Bar chart showing buckling load for 0.8 mm face sheet mesh study](chart)

### 1,5 mm - CPS4

<table>
<thead>
<tr>
<th>Mesh height (mscy) [mm]</th>
<th>15</th>
<th>7,5</th>
<th>5</th>
<th>1,5</th>
<th>0,15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements height [-]</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Elements over width:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 [N]</td>
<td>1576,1</td>
<td>1140,1</td>
<td>1055,3</td>
<td>482,6</td>
<td>480,3</td>
</tr>
<tr>
<td>10 [N]</td>
<td>1561,2</td>
<td>1117,5</td>
<td>1032,0</td>
<td>441,9</td>
<td>439,8</td>
</tr>
<tr>
<td>30 [N]</td>
<td>1553,1</td>
<td>1104,8</td>
<td>1018,9</td>
<td>416,9</td>
<td>414,9</td>
</tr>
<tr>
<td>50 [N]</td>
<td>1552,5</td>
<td>1103,7</td>
<td>1017,8</td>
<td>414,6</td>
<td>412,5</td>
</tr>
</tbody>
</table>

**1,5 mm face sheet mesh study**

![Bar chart showing buckling load for 1.5 mm face sheet mesh study](chart)
<table>
<thead>
<tr>
<th>System length</th>
<th>[ mm ]</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>B23 mesh size (msf)</td>
<td>[ mm ]</td>
<td>1</td>
</tr>
</tbody>
</table>

### 3,0 mm - CPS4

<table>
<thead>
<tr>
<th>Mesh height (mscy)</th>
<th>[ mm ]</th>
<th>15</th>
<th>7,5</th>
<th>5</th>
<th>1,5</th>
<th>0,15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements height</td>
<td>[- ]</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>100</td>
<td>1000</td>
</tr>
</tbody>
</table>

Elements over width:

<table>
<thead>
<tr>
<th></th>
<th>[ N ]</th>
<th>3856,3</th>
<th>2233,1</th>
<th>2032,5</th>
<th>813,4</th>
<th>812,2</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td></td>
<td>3847,3</td>
<td>2222,4</td>
<td>2021,4</td>
<td>789,8</td>
<td>788,6</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>3842,6</td>
<td>2216,7</td>
<td>2015,6</td>
<td>776,6</td>
<td>775,4</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>3842,2</td>
<td>2216,3</td>
<td>2015,1</td>
<td>775,4</td>
<td>774,2</td>
</tr>
<tr>
<td>50</td>
<td></td>
<td>3842,6</td>
<td>2216,7</td>
<td>2015,6</td>
<td>776,6</td>
<td>775,4</td>
</tr>
</tbody>
</table>

3,0 mm face sheet mesh study

![Graph showing buckling load vs. amount of elements over system length](image-url)
Core mesh width sensitivity analysis - System length 2650 mm - CPS4

System length [ mm ] 2650

B23 mesh size (msf) [ mm ] 1

0,8 mm - CPS4

Mesh height (mscy) [ mm ] 100 50 30 10 7,5 5
Elements height [ - ] 26,5 53 88,3 265 353,3 530

Elements over width:

<table>
<thead>
<tr>
<th></th>
<th>6</th>
<th>10</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>130,2</td>
<td>128,7</td>
<td>128,3</td>
</tr>
<tr>
<td>10</td>
<td>130,2</td>
<td>128,7</td>
<td>128,2</td>
</tr>
<tr>
<td>30</td>
<td>130,2</td>
<td>128,7</td>
<td>128,2</td>
</tr>
</tbody>
</table>

0,8 mm face sheet mesh study

1,5 mm - CPS4

Mesh height (mscy) [ mm ] 100 50 30 10 7,5 5
Elements height [ - ] 26,5 53 88,3 265 353,3 530

Elements over width:

<table>
<thead>
<tr>
<th></th>
<th>6</th>
<th>10</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>171,7</td>
<td>169,5</td>
<td>168,7</td>
</tr>
<tr>
<td>10</td>
<td>171,7</td>
<td>169,5</td>
<td>168,7</td>
</tr>
<tr>
<td>30</td>
<td>171,7</td>
<td>169,5</td>
<td>168,6</td>
</tr>
</tbody>
</table>

1,5 mm face sheet mesh study
<table>
<thead>
<tr>
<th>System length [mm]</th>
<th>2650</th>
</tr>
</thead>
<tbody>
<tr>
<td>B23 mesh size (msf) [mm]</td>
<td>1</td>
</tr>
<tr>
<td><strong>Euler/shear buckling</strong></td>
<td></td>
</tr>
</tbody>
</table>

**3,0 mm - CPS4**

<table>
<thead>
<tr>
<th>Mesh height (mscy) [mm]</th>
<th>100</th>
<th>50</th>
<th>30</th>
<th>10</th>
<th>7,5</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements height [-]</td>
<td>26,5</td>
<td>53</td>
<td>88,3</td>
<td>265</td>
<td>353,3</td>
<td>530</td>
</tr>
<tr>
<td>Elements over width:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 [N]</td>
<td>307,1</td>
<td>295,8</td>
<td>291,1</td>
<td>287,8</td>
<td>286,9</td>
<td>286,6</td>
</tr>
<tr>
<td>10 [N]</td>
<td>307,1</td>
<td>295,8</td>
<td>291,1</td>
<td>287,8</td>
<td>286,9</td>
<td>286,6</td>
</tr>
<tr>
<td>30 [N]</td>
<td>307,1</td>
<td>295,8</td>
<td>291,1</td>
<td>287,8</td>
<td>286,9</td>
<td>286,6</td>
</tr>
</tbody>
</table>

### 3,0 mm face sheet mesh study

<table>
<thead>
<tr>
<th>Amount of elements over system length</th>
</tr>
</thead>
<tbody>
<tr>
<td>26,5</td>
</tr>
<tr>
<td>53</td>
</tr>
<tr>
<td>88,3</td>
</tr>
<tr>
<td>265</td>
</tr>
<tr>
<td>353,3</td>
</tr>
<tr>
<td>530</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Buckling load [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>275</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>
### Core mesh height sensitivity analysis - System length 150 mm - CPS4 and CPS8

<table>
<thead>
<tr>
<th>System length [mm]</th>
<th>150</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>CPS4 width (mscx) [mm]</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>B23 mesh size (msf) [mm]</td>
<td>1</td>
</tr>
</tbody>
</table>

#### 0.8 mm

<table>
<thead>
<tr>
<th>Size [mm]</th>
<th>15,0</th>
<th>7,5</th>
<th>5,0</th>
<th>3,0</th>
<th>1,5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements  [-]</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>CPS4 [N]</td>
<td>887,68</td>
<td>663,99</td>
<td>626,52</td>
<td>514,49</td>
<td>302,44</td>
</tr>
<tr>
<td>CPS8 [N]</td>
<td>317,06</td>
<td>285,9</td>
<td>271,82</td>
<td>262,83</td>
<td>258,8</td>
</tr>
</tbody>
</table>

#### 0.8 mm face sheet mesh study

![Graph](image1)

#### 1.5 mm

<table>
<thead>
<tr>
<th>Size [mm]</th>
<th>15,0</th>
<th>7,5</th>
<th>5,0</th>
<th>3,0</th>
<th>1,5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements  [-]</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>CPS4 [N]</td>
<td>1561,2</td>
<td>1117,5</td>
<td>1032</td>
<td>824,63</td>
<td>441,93</td>
</tr>
<tr>
<td>CPS8 [N]</td>
<td>466,46</td>
<td>431,92</td>
<td>421,79</td>
<td>415,77</td>
<td>413,01</td>
</tr>
</tbody>
</table>

#### 1.5 mm face sheet mesh study

![Graph](image2)
System length [mm] 150

CPS4 width (mscx) [mm] 15
B23 mesh size (msf) [mm] 1

### 3,0 mm

<table>
<thead>
<tr>
<th>Size  [mm]</th>
<th>15,0</th>
<th>7,5</th>
<th>5,0</th>
<th>3,0</th>
<th>1,5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements  [-]</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>CPS4 [N]</td>
<td>3847,3</td>
<td>2222,4</td>
<td>2021,4</td>
<td>1595,1</td>
<td>789,82</td>
</tr>
<tr>
<td>CPS8 [N]</td>
<td>837,65</td>
<td>788,95</td>
<td>779,8</td>
<td>775,67</td>
<td>774,04</td>
</tr>
</tbody>
</table>

![Graph](image)

### CPS8 elements distribution

CPS8 width (mscx) [mm] 15
B23 mesh size (msf) [mm] 1

<table>
<thead>
<tr>
<th>Size [mm]</th>
<th>15,0</th>
<th>7,5</th>
<th>5,0</th>
<th>3,0</th>
<th>1,5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements  [-]</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>0,8 mm [N]</td>
<td>317,06</td>
<td>285,9</td>
<td>271,82</td>
<td>262,83</td>
<td>258,8</td>
</tr>
<tr>
<td>1,5 mm [N]</td>
<td>466,46</td>
<td>431,92</td>
<td>421,79</td>
<td>415,77</td>
<td>413,01</td>
</tr>
<tr>
<td>3,0 mm [N]</td>
<td>837,65</td>
<td>788,95</td>
<td>779,8</td>
<td>775,67</td>
<td>774,04</td>
</tr>
</tbody>
</table>

![Graph](image)

### CPS8 elements
### Core mesh height sensitivity analysis - System length 2650 mm - CPS4 and CPS8

<table>
<thead>
<tr>
<th>System length</th>
<th>[ mm ]</th>
<th>2650</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPS4 width (mscx)</td>
<td>[ mm ]</td>
<td>15</td>
</tr>
<tr>
<td>B23 mesh size (msf)</td>
<td>[ mm ]</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>0.8 mm - CPS4</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>[ mm ]</td>
<td>200,0</td>
<td>50,0</td>
<td>40,0</td>
<td>25,0</td>
<td>20,0</td>
<td>15,0</td>
<td>10,0</td>
<td>7,5</td>
<td>5,0</td>
</tr>
<tr>
<td>Elements</td>
<td>[- ]</td>
<td>13,25</td>
<td>53</td>
<td>66,25</td>
<td>106</td>
<td>132,5</td>
<td>176,7</td>
<td>265</td>
<td>353,3</td>
<td>530</td>
</tr>
<tr>
<td>Mode 1</td>
<td>[ N ]</td>
<td>136,96</td>
<td>128,66</td>
<td>128,42</td>
<td>128,18</td>
<td>128,05</td>
<td>128,01</td>
<td>127,98</td>
<td>127,96</td>
<td></td>
</tr>
<tr>
<td>Mode 2</td>
<td>[ N ]</td>
<td>452,59</td>
<td>420,63</td>
<td>419,69</td>
<td>418,74</td>
<td>418,4</td>
<td>418,16</td>
<td>417,97</td>
<td>417,81</td>
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</tbody>
</table>

#### 0.8 mm face sheet mesh study

![Graph showing Buckling load vs. amount of elements for 0.8 mm face sheet mesh study](chart0.8mm.png)

<table>
<thead>
<tr>
<th>1.5 mm - CPS4</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>[ mm ]</td>
<td>200,0</td>
<td>50,0</td>
<td>40,0</td>
<td>25,0</td>
<td>20,0</td>
<td>15,0</td>
<td>10,0</td>
<td>7,5</td>
<td>5,0</td>
</tr>
<tr>
<td>Elements</td>
<td>[- ]</td>
<td>13,25</td>
<td>53</td>
<td>66,25</td>
<td>106</td>
<td>132,5</td>
<td>176,7</td>
<td>265</td>
<td>353,3</td>
<td>530</td>
</tr>
<tr>
<td>Mode 1</td>
<td>[ N ]</td>
<td>180,16</td>
<td>169,49</td>
<td>168,99</td>
<td>168,57</td>
<td>168,34</td>
<td>168,2</td>
<td>168,1</td>
<td>167,97</td>
<td>167,93</td>
</tr>
<tr>
<td>Mode 2</td>
<td>[ N ]</td>
<td>567,76</td>
<td>527,84</td>
<td>525,76</td>
<td>523,93</td>
<td>522,9</td>
<td>522,23</td>
<td>521,64</td>
<td>521</td>
<td></td>
</tr>
</tbody>
</table>

#### 1.5 mm face sheet mesh study

![Graph showing Buckling load vs. amount of elements for 1.5 mm face sheet mesh study](chart1.5mm.png)
### 3.0 mm - CPS4

<table>
<thead>
<tr>
<th>Size [mm]</th>
<th>200.0</th>
<th>50.0</th>
<th>40.0</th>
<th>25.0</th>
<th>20.0</th>
<th>15.0</th>
<th>10.0</th>
<th>7.5</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements  [-]</td>
<td>13,25</td>
<td>53</td>
<td>66,25</td>
<td>106</td>
<td>132,5</td>
<td>176,7</td>
<td>265</td>
<td>353,3</td>
<td>530</td>
</tr>
<tr>
<td>Mode 1 [N]</td>
<td>335.33</td>
<td>295.76</td>
<td>292.93</td>
<td>290.9</td>
<td>289.36</td>
<td>288.49</td>
<td>287.8</td>
<td>286.86</td>
<td>286.57</td>
</tr>
<tr>
<td>Mode 2 [N]</td>
<td>990.23</td>
<td>819.25</td>
<td>807.14</td>
<td>797.77</td>
<td>790.8</td>
<td>786.86</td>
<td>783.2</td>
<td>778.79</td>
<td>777.37</td>
</tr>
</tbody>
</table>

### 0.8 mm - CPS8

<table>
<thead>
<tr>
<th>Size [mm]</th>
<th>200.0</th>
<th>50.0</th>
<th>40.0</th>
<th>25.0</th>
<th>20.0</th>
<th>15.0</th>
<th>10.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements  [-]</td>
<td>13,25</td>
<td>53</td>
<td>66,25</td>
<td>106</td>
<td>132,5</td>
<td>176,7</td>
<td>265</td>
</tr>
<tr>
<td>Mode 1 [N]</td>
<td>127.97</td>
<td>127.94</td>
<td>127.94</td>
<td>127.94</td>
<td>127.94</td>
<td>128.05</td>
<td>128.05</td>
</tr>
<tr>
<td>Mode 2 [N]</td>
<td>418.17</td>
<td>417.77</td>
<td>417.72</td>
<td>393.68</td>
<td>371.77</td>
<td>418.16</td>
<td>417.97</td>
</tr>
</tbody>
</table>
System length [mm] 2650

CPS8 width (mscx) [mm] 15
B23 mesh size (msf) [mm] 1

1,5 mm - CPS8

<table>
<thead>
<tr>
<th>Size [mm]</th>
<th>200,0</th>
<th>50,0</th>
<th>40,0</th>
<th>25,0</th>
<th>20,0</th>
<th>15,0</th>
<th>7,5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements [-]</td>
<td>13,25</td>
<td>53</td>
<td>66,25</td>
<td>106</td>
<td>132,5</td>
<td>176,7</td>
<td>353</td>
</tr>
<tr>
<td>Mode 2 [N]</td>
<td>522,72</td>
<td>520,63</td>
<td>520,55</td>
<td>459,81</td>
<td>452,94</td>
<td>444,15</td>
<td>444,15</td>
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</table>

3,0 mm - CPS8

<table>
<thead>
<tr>
<th>Size [mm]</th>
<th>200,0</th>
<th>50,0</th>
<th>40,0</th>
<th>25,0</th>
<th>20,0</th>
<th>15,0</th>
<th>7,5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements [-]</td>
<td>13,25</td>
<td>53</td>
<td>66,25</td>
<td>106</td>
<td>132,5</td>
<td>176,7</td>
<td>353,3</td>
</tr>
<tr>
<td>Mode 2 [N]</td>
<td>990,23</td>
<td>819,25</td>
<td>807,14</td>
<td>797,77</td>
<td>763,29</td>
<td>748,34</td>
<td>730,13</td>
</tr>
</tbody>
</table>
Mesh size sensitivity analysis - Face sheet B23 - System length 150 mm

System length [mm] 150

CPS4 mesh size:
Width (mscx) = height (mscy) = B23 size (msf)

<table>
<thead>
<tr>
<th>msf</th>
<th>0.8 mm</th>
<th>13</th>
<th>15,00</th>
<th>12,50</th>
<th>9,375</th>
<th>7,50</th>
<th>5,00</th>
<th>1,50</th>
<th>0,50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements</td>
<td>10</td>
<td>12</td>
<td>16</td>
<td>20</td>
<td>30</td>
<td>100</td>
<td>300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode 1</td>
<td>65,34</td>
<td>91,451</td>
<td>156,66</td>
<td>201,88</td>
<td>230,13</td>
<td>253,83</td>
<td>256,17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode 2</td>
<td>65,341</td>
<td>91,451</td>
<td>156,66</td>
<td>201,88</td>
<td>230,14</td>
<td>253,85</td>
<td>256,18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Half sine waves mode 1: Solution converged

<table>
<thead>
<tr>
<th>Mode 1</th>
<th>Mode 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>65,34</td>
<td>91,451</td>
</tr>
<tr>
<td>156,66</td>
<td>201,88</td>
</tr>
<tr>
<td>230,13</td>
<td>253,83</td>
</tr>
<tr>
<td>256,17</td>
<td>256,18</td>
</tr>
</tbody>
</table>

0.8 mm face sheet mesh study

Buckling load [N]

Amount of elements over length
CPS4 mesh size:
Width (mscx) = height (mscy) = B23 size (msf)

### Half sine waves mode 1:

<table>
<thead>
<tr>
<th>System length [mm]</th>
<th>Solution converged</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 mm msf</td>
<td></td>
</tr>
<tr>
<td>Elements</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 12 16 20 30 100 300</td>
</tr>
<tr>
<td>Mode 1</td>
<td>275.96 328.23 361.92 378.28 396.32 410.98 412.33</td>
</tr>
<tr>
<td>Mode 2</td>
<td>275.96 328.23 361.94 378.28 396.32 410.98 412.34</td>
</tr>
</tbody>
</table>

### 1.5 mm face sheet mesh study

![Graph showing buckling load vs amount of elements over length for different modes and element counts.]

### Half sine waves mode 1:

<table>
<thead>
<tr>
<th>System length [mm]</th>
<th>Solution converged</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 mm msf</td>
<td></td>
</tr>
<tr>
<td>Elements</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 12 16 20 30 100 300</td>
</tr>
<tr>
<td>Mode 1</td>
<td>707.2 725.4 745.53 755.63 766.07 773.46 774.1</td>
</tr>
<tr>
<td>Mode 2</td>
<td>708.15 726.47 746.77 756.28 766.12 773.87 774.51</td>
</tr>
</tbody>
</table>

### 3.0 mm face sheet mesh study

![Graph showing buckling load vs amount of elements over length for different modes and element counts.]

Wrinkling
Mesh size sensitivity analysis - Face sheet B23 - System length 2650 mm

System length [ mm ] 2650

CPS4 mesh size:
Width (mscx) = height (mscy) = B23 size (msf)

Amount of elements are able to describe wrinkling wavelength:

<table>
<thead>
<tr>
<th>0.8 mm</th>
<th>No</th>
<th>No</th>
<th>Yes</th>
<th>Yes</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>msf</td>
<td>10,00</td>
<td>7,50</td>
<td>5,00</td>
<td>2,00</td>
<td>1,00</td>
</tr>
<tr>
<td>Elements</td>
<td>265,0</td>
<td>353,3</td>
<td>530,0</td>
<td>1325,0</td>
<td>2650,0</td>
</tr>
<tr>
<td>Mode 1</td>
<td>127,94</td>
<td>127,93</td>
<td>127,92</td>
<td>127,92</td>
<td>127,92</td>
</tr>
<tr>
<td>Mode 2</td>
<td>136,04</td>
<td>197,94</td>
<td>226,2</td>
<td>247,53</td>
<td>253,78</td>
</tr>
</tbody>
</table>

0.8 mm face sheet mesh study

Euler/shear
Wrinkling

Wavelength
CPS4 mesh size:
Width (mscx) = height (mscy) = B23 size (msf)

**Wrinkling**

Amount of elements are able to describe wrinkling wavelength:

<table>
<thead>
<tr>
<th>msf</th>
<th>1.5 mm</th>
<th>3.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>15.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Elements</td>
<td>176.7</td>
<td>265.0</td>
</tr>
<tr>
<td>Mode 1</td>
<td>167.81</td>
<td>167.79</td>
</tr>
<tr>
<td>Mode 2</td>
<td>272.12</td>
<td>346.02</td>
</tr>
</tbody>
</table>

**System length**

[mm] 2650

**Euler/shear**

1.5 mm face sheet mesh study

![Graph showing buckling load vs. amount of elements over length for 1.5 mm face sheet mesh study.](image)

3.0 mm face sheet mesh study

![Graph showing buckling load vs. amount of elements over length for 3.0 mm face sheet mesh study.](image)
Benchmark sandwich panel $L = 2650$ mm

**Input 2D Eigenvalue problem**

- $L = 2650$ [mm]
- $D = 900$ [mm]
- $c = 150$ [mm]
- $E = 30$ [Mpa]
- $v = 0,33$ [-]
- $G = 11,28$ [Mpa]

B23 face sheet elements
CPS4 or CPS8 core elements

**Analytical buckling loads**

<table>
<thead>
<tr>
<th>Face sheet thickness ($t$)</th>
<th>[mm]</th>
<th>0,8</th>
<th>1,5</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_i$ core</td>
<td>[Nmm²]</td>
<td>7,72E+09</td>
<td>7,82E+09</td>
<td>8,06E+09</td>
</tr>
<tr>
<td>$E_i$ face sheet</td>
<td>[Nmm²]</td>
<td>3,84E+01</td>
<td>2,53E+02</td>
<td>2,03E+03</td>
</tr>
<tr>
<td>$E_A a^2$ face sheet</td>
<td>[Nmm²]</td>
<td>1,23E+08</td>
<td>2,32E+08</td>
<td>4,74E+08</td>
</tr>
<tr>
<td>$E_i$ sandwich</td>
<td>[Nmm²]</td>
<td>7,96E+09</td>
<td>8,29E+09</td>
<td>9,01E+09</td>
</tr>
<tr>
<td>$P_{cr} E_i$ sandwich</td>
<td>[N]</td>
<td>11189</td>
<td>11649</td>
<td>12658</td>
</tr>
<tr>
<td>$P_{cr}$ AG core</td>
<td>[N]</td>
<td>1530677</td>
<td>1537782</td>
<td>1553008</td>
</tr>
<tr>
<td>$P_{cr} = 1/((1/P_{cr} E_i)+(1/P_{cr} AG))$</td>
<td>[N]</td>
<td>11108</td>
<td>11561</td>
<td>12556</td>
</tr>
</tbody>
</table>

**FEM GL analysis**

<table>
<thead>
<tr>
<th>Face sheet thickness ($t$)</th>
<th>[mm]</th>
<th>0,8</th>
<th>1,5</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{cr}$ CPS4</td>
<td>[N]</td>
<td>11195</td>
<td>11603</td>
<td>12546</td>
</tr>
<tr>
<td>Difference</td>
<td>[%]</td>
<td>0,78</td>
<td>0,36</td>
<td>-0,08</td>
</tr>
<tr>
<td>$P_{cr}$ CPS8</td>
<td>[N]</td>
<td>11177</td>
<td>11579</td>
<td>12514</td>
</tr>
<tr>
<td>Difference</td>
<td>[%]</td>
<td>0,62</td>
<td>0,15</td>
<td>-0,33</td>
</tr>
</tbody>
</table>

The percentage values are the differences with respect to the reference solution of the analytical buckling load. The differences satisfy to the assumption of one percent or less.
APPENDIX K  IMPERFECTION SENSITIVITY ANALYSIS SHORT PANELS
Imperfection sensitivity analysis short sandwich panel

The initial imperfection is analysed in the imperfection sensitivity analysis with respect to the force-axial shortening diagrams of the experimental test results. The FE model of the short sandwich panels (Figure 2) is used with a variable initial imperfection and a constant face sheet compression modulus of elasticity per face sheet thickness. In this analysis the face sheet compression modulus is assumed to be equal to the face sheet tensile modulus of elasticity while the initial imperfection has an amplitude by ratio to the face sheet thickness.

An important observation can be made to figure 3 and figure 4. If the initial imperfection in the force-axial shortening diagram changes, also changes the curve that describes the axial stiffness behaviour and the slope of that curve. As mentioned in the thesis, the face sheet compression modulus also affects the slope but is considered out of scope in this analysis. In the initial branch of the force-axial shortening diagrams wherein the load is applied to the sandwich panel the slope is nonlinear. Regardless of this initial nonlinear branch in the diagram the slope of the individual experimental test results vary (Figure 3, experimental tests 41 to 44). Furthermore, the test results describe a nonlinear axial stiffness behaviour. In contrast to the sandwich panels with a face sheet thickness of 1,5 mm and 3,0 mm the deviation between the individual test results of a sandwich panel with face sheets of 0,8 mm are larger. This indicates that face sheets of 0,8 mm are more sensitive to initial imperfections rather than thick face sheets. The initial imperfections of the sandwich panel are based on the variation within the test results and on the linear or nonlinear branch of the test results. The initial imperfection of thin face sheets of 0,8 mm is assumed [1], [2] to ten percent of the face sheet thickness.

Again, regardless of the initial nonlinear branch in the diagrams (Figure 3, lower diagram and figure 4) the slopes of the experimental test results are similar and linear up to the occurrence of the first wrinkle. At a wrinkle the curve of the test result changes. According to the test results the sandwich panels with face sheets of 1,5 mm and 3,0 mm are less sensitive to initial imperfections than face sheets of 0,8 mm. The equal linear slopes of the test results (1,5 mm and 3,0 mm) indicate a perfect linear framework. An initial imperfection of ten percent of the face sheet thickness is a safe assumption but too large to the face sheet thicknesses of 1,5 mm and 3,0 mm. The initial imperfections these face sheets are respectively 0,001 mm (or 0,1% of the face sheet thickness) and 0,05 mm (or 1,67% of the face sheet thickness). These geometrical imperfections (Table 1) are assigned to the amplitudes of the buckling modes.

The initial imperfections are small with respect to local instabilities but can be larger to global instability modes. Furthermore, the scale or size of the sandwich panel also determines the size of the initial imperfection.

Table 1: Geometrical initial imperfections

<table>
<thead>
<tr>
<th>Imperfection [ mm ]</th>
<th>Face sheet t = 0,8 mm</th>
<th>Face sheet t = 1,5 mm</th>
<th>Face sheet t = 3,0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,088 or t/10</td>
<td>0,001</td>
<td>0,05</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3: Above force-axial shortening diagram sandwich panel of 0.8 mm face sheet thickness and below of 1.5 mm.
STABILITY OF AXIALLY LOADED GFRP SANDWICH WALL PANELS

Figure 4: Force-axial shortening diagram of sandwich panel with face sheets of 3.0 mm.


Figure 5: Above: Force-axial shortening diagram (face sheet thickness 0.8 mm). Below: Force-axial shortening diagram (face sheet thickness 3.0 mm). Continuous lines are the experimental tests and the dotted lines represent the FEM GNL analysis with a varying face sheet modulus of elasticity.
APPENDIX L  IMPERFECTION SENSITIVITY ANALYSIS LARGE PANELS
Imperfection sensitivity analysis large sandwich panel

Imperfections of the first and second buckling modes are varied and assigned to the geometry of Figure 6. Each face sheet thickness contains four diagrams:

- mode 1 load-axial shortening diagram
- mode 1 load-out-of-plane deformation diagram
- mode 2 load-axial shortening diagram
- mode 2 load-out-of-plane deformation diagram

Figure 6: Geometry
Sandwich panel with 0.8 mm face sheet (Figure 7)

Figure 7: Mode 1 variable imperfections. Top: Force-axial shortening diagram. Bottom: Force-out-of-plane deformation diagram
Sandwich panel with 1,5 mm face sheet (Figure 8 and figure 9)

Figure 8: Mode 1 variable imperfections. Top: Load-axial shortening diagram. Bottom: Load-out-of-plane deformation diagram.
Figure 9: Mode 2 variable imperfections. Top: Load-axial shortening diagram. Bottom: Load-out-of-plane deformation diagram.
Sandwich panel with 3,0 mm face sheet (Figure 10 and Figure 11)

Figure 10: Mode 1 variable imperfections. Top: Load-axial shortening diagram. Bottom: Load-out-of-plane deformation diagram
Figure 11: Mode 2 variable imperfections. Top: Load-axial shortening diagram. Bottom: Load-out-of-plane deformation diagram
```python
# -*- coding: mbcs -*-
from part import *
from material import *
from section import *
from assembly import *
from step import *
from interaction import *
from load import *
from mesh import *
from optimization import *
from job import *
from sketch import *
from visualization import *
from connectorBehavior import *

#------------------------- LINEAR BUCKLING ANALYSIS --------------------------
#
#------------------------- PARAMETERS CAN BE CHANGED -------------------------
#
# Predefined model names are GFRP = ('GFRP08', 'GFRP15', 'GFRP30')
# Model name
GFRP = ('GFRP30',)

# Geometry system
L = 2650.0            # System length
D = 900.0            # Depth system
Kr = 1.0e-06         # Rotational spring stiffness supports: Kr = M/Phi (Nmm/Rad)

# Core
c = 150.0            # Thickness
Ec = 30.0            # Modulus of elasticity
vc = 0.33            # Poisson ratio

# GL step
SE = 2               # Step; number of requested eigenvalues
SV = 20              # Step; number of vectors
SI = 150             # Step; Maximum iterations

#------------------------- MODEL ---------------------------------------------
#
for x1 in GFRP:
    mymodel = mdb.Model(modelType=STANDARD_EXPLICIT, name='GL_:'+x1)
    if 'Model-1' in mdb.models: del mdb.models['Model-1']
    session.graphicsOptions.setValue(backgroundStyle=SOLID, backgroundColor='#FFFFFF')
    vp = session.viewport('Viewport: 1')
    vp.viewportAnnotationOptions.setValue(title=OFF, state=ON,
    legendFont='--verdana-medium-r-normal-*-*-140-*-*-p-*-*-*',
    stateFont='--verdana-medium-r-normal-*-*-140-*-*-p-*-*-*',
    annotations=ON, compass=OFF)
```
# Face sheet parameters

```python
if x1 == 'GFRP08':
    t = 0.88  # Thickness
    Ef = 8932.0  # Modulus of elasticity
    vf = 0.37  # Poisson ratio
    mscx = 15.0  # Mesh size x-direction
    mscy = 5.0  # Mesh size core y-direction = mesh size face sheet y-direction
elif x1 == 'GFRP15':
    t = 1.5
    Ef = 5900.0
    vf = 0.1
    mscx = 15.0
    mscy = 7.5
elif x1 == 'GFRP30':
    t = 2.91
    Ef = 6345.0
    vf = 0.27
    mscx = 15.0
    mscy = 10.0
```

# Part geometry

```python
mymodel.ConstrainedSketch(name='__profile__', sheetSize=200.0)
mymodel.sketches['__profile__'].rectangle(point1=(0.0, 0.0),
    point2=(float(c)+float(t), float(L)))
mymodel.Part(dimensionality=TWO_D_PLANAR, name='Core', type=DEFORMABLE_BODY)
mymodel.parts['Core'].BaseShell(sketch=
    mymodel.sketches['__profile__'])
del mymodel.sketches['__profile__']
```

# Surface

```python
mymodel.parts['Core'].Surface(name='Surf-1 Top edge', side1Edges=
    mymodel.parts['Core'].edges.getSequenceFromMask('([#4 ], ), ))
mymodel.parts['Core'].Surface(name='Surf-2 Bottom edge',
    side1Edges=mymodel.parts['Core'].edges.getSequenceFromMask('([#1 ], ), ))
mymodel.parts['Core'].Surface(name='Surf-3 Left edge',
    side1Edges=mymodel.parts['Core'].edges.getSequenceFromMask('([#8 ], ), ))
mymodel.parts['Core'].Surface(name='Surf-4 Right edge',
    side1Edges=mymodel.parts['Core'].edges.getSequenceFromMask('([#2 ], ), ))
```

# Material

```python
mymodel.Material(name='XPS-FL')
mymodel.materials['XPS-FL'].Elastic(table=((float(Ec), float(vc)), ))
```
# Section
```python
mymodel.HomogeneousSolidSection(material='XPS-FL', name='Core',
    thickness=float(D))
mymodel.parts['Core'].Set(faces=
    mymodel.parts['Core'].faces.getSequenceFromMask((['#1'],),
    ), name='Set-1')
```

# Section Assignment
```python
mymodel.parts['Core'].SectionAssignment(offset=0.0, offsetField='",
    offsetType=MIDDLE_SURFACE, region=
    mymodel.parts['Core'].sets['Set-1'], sectionName='Core',
    thicknessAssignment=FROM_SECTION)
```

# Mesh - Assign element type, Assign Mesh Controls, Seed part, Mesh part
```python
mymodel.parts['Core'].setElementType(elemTypes=(ElemType(
    elemCode=CPS4, elemLibrary=STANDARD),
    ElemType(elemCode=CPS3, elemLibrary=STANDARD)),
    regions=()
    mymodel.parts['Core'].faces.getSequenceFromMask((['#1'],),
    ),

mymodel.parts['Core'].setMeshControls(elemShape=QUAD, regions=
    mymodel.parts['Core'].faces.getSequenceFromMask((['#1'],),
    ),
    technique=STRUCTURED)

mymodel.parts['Core'].seedEdgeBySize(constraint=FINER,
    deviationFactor=0.1, edges=
    mymodel.parts['Core'].edges.getSequenceFromMask((['#5'],),
    ),
    size=float(mscx))

mymodel.parts['Core'].seedEdgeBySize(constraint=FINER,
    deviationFactor=0.1, edges=
    mymodel.parts['Core'].edges.getSequenceFromMask((['#a'],),
    ),
    size=float(mscy))

mymodel.parts['Core'].generateMesh()
```

# Automatic generated set from mesh
```python
mymodel.parts['Core'].Set(name='Middle', nodes=
    mymodel.parts['Core'].nodes.getBoundingBox(
    xMin = (-1.0e-6), yMin = ((float(L)/2)-(float(mscy)*0.75)),
    xMax = (float(c)+(2*float(t))), yMax = (((float(L)/2)+(1.0e-6))))
```

------------------------ FACE SHEET ------------------------

# Part geometry
```python
mymodel.ConstrainedSketch(name='__profile__', sheetSize=200.0)
mymodel.sketches['__profile__'].Line(point1=(0.0, 0.0), point2=(0.0, float(L)))
mymodel.sketches['__profile__'].VerticalConstraint(addUndoState=False, entity=mymodel.sketches['__profile__'].geometry[2])
mymodel.Part(dimensionality=TWO_D_PLANAR, name='Face sheet', type=DEFORMABLE_BODY)
mymodel.parts['Face sheet'].BaseWire(sketch=
    mymodel.sketches['__profile__'])
del mymodel.sketches['__profile__']
```

# Surface
mymodel.parts['Face sheet'].Surface(name='Surf-1 Xneg', side1Edges=mymodel.parts['Face sheet'].edges.getSequenceFromMask(( '[#1 ]', ), ))
mymodel.parts['Face sheet'].Surface(name='Surf-2 Xpos', side2Edges=mymodel.parts['Face sheet'].edges.getSequenceFromMask(( '[#1 ]', ), ))

# Surf-Yneg = Y negative according to global coordinate axisdirection
# Surf-Ypos = Y positive according to global coordinate axisdirection

# Set
mymodel.parts['Face sheet'].Set(name='Set-2 Yneg', vertices=mymodel.parts['Face sheet'].vertices.getSequenceFromMask(( '[#1 ]', ), ))
mymodel.parts['Face sheet'].Set(name='Set-3 Ypos', vertices=mymodel.parts['Face sheet'].vertices.getSequenceFromMask(( '[#2 ]', ), ))

# Material
mymodel.Material(name='GFRP-FL')
mymodel.materials['GFRP-FL'].Elastic(table=((float(Ef), float(vf)), ))

# Section
mymodel.RectangularProfile(a=float(D), b=float(t), name='Profile-1')
mymodelBeamSection(consistentMassMatrix=False, integration=DURING_ANALYSIS, material='GFRP-FL', name='Face sheet', poissonRatio=0.0, profile='Profile-1', temperatureVar=LINEAR)

# Section Assignment
mymodel.parts['Face sheet'].Set(edges=mymodel.parts['Face sheet'].edges.getSequenceFromMask(( '[#7 ]', ), ), name='Set-1')
mymodel.parts['Face sheet'].SectionAssignment(offset=0.0, offsetField='', offsetType=MIDDLE_SURFACE, region=mymodel.parts['Face sheet'].sets['Set-1'], sectionName='Face sheet', thicknessAssignment=FROM_SECTION)

# AssignBeamSectionOrientation (only applicable to wires)
mymodel.parts['Face sheet'].assignBeamSectionOrientation(method=N1_COSINES, n1=(0.0, 0.0, -1.0), region=mymodel.parts['Face sheet'].sets['Set-1'])

# Mesh - Assign element type, Seed part, Mesh part
mymodel.parts['Face sheet'].setElementType(elemTypes=(ElemType(elemCode=B23, elemLibrary=STANDARD), ), regions=(mymodel.parts['Face sheet'].edges.getSequenceFromMask(( '[#1 ]', ), ), ))
mymodel.parts['Face sheet'].seedPart(deviationFactor=0.1, minSizeFactor=0.1, size=float(mscy))
mymodel.parts['Face sheet'].generateMesh()

# Automatic generated set from mesh
mymodel.parts['Face sheet'].Set(name='Middle', nodes=
# Instance - Rotate and translate
mymodel.rootAssembly.translate(instanceList=('Core-1', ),
vector=((float(l)/2), 0.0, 0.0))
mymodel.rootAssembly.translate(instanceList=('Face sheet-1', ),
vector=((float(l)/2), 0.0, 0.0))
mymodel.rootAssembly.translate(instanceList=('Face sheet-2', ),
vector=((float(c)+(float(l)/2)), 0.0, 0.0))
mymodel.rootAssembly.translate(instanceList=['Rigid-Yneg',],
    vector=((float(c)*-1), -10.0, 0.0))
mymodel.rootAssembly.rotate(angle=180.0, axisDirection=(0.0, 0.0, 1.0), axisPoint=(0.0, 0.0, 0.0), instanceList=['Rigid-Ypos',])
mymodel.rootAssembly.translate(instanceList=['Rigid-Ypos',],
    vector=((float(c)+float(t)), (float(L)+10.0), 0.0))

# Feature
mymodel.rootAssembly.ReferencePoint(point=((float(c)/2), -100.0, 0.0))
mymodel.rootAssembly.features.changeKey(fromName='RP-1',
    toName='RP Yneg')
mymodel.rootAssembly.ReferencePoint(point=((float(c)/2), (float(L)+100.0), 0.0))
mymodel.rootAssembly.features.changeKey(fromName='RP-1',
    toName='RP Ypos')

# Set
mymodel.rootAssembly.Set(name='BC RP Yneg', referencePoints=(
    mymodel.rootAssembly.referencePoints[12], ))
mymodel.rootAssembly.Set(name='BC RP Ypos', referencePoints=(
    mymodel.rootAssembly.referencePoints[13], ))
mymodel.rootAssembly.Set(edges=
    mymodel.rootAssembly.instances['Core-1'].edges.getSequenceFromMask(
        {'[#4 ]', }, ), name='s-Set-Ypos', vertices=
    mymodel.rootAssembly.instances['Face sheet-1'].vertices.getSequenceFromMask(
        mask=('[#2 ]', ), )+)
)mymodel.rootAssembly.instances['Face sheet-2'].vertices.getSequenceFromMask(
    mask=('[#2 ]', ), ))
)mymodel.rootAssembly.Set(edges=
    mymodel.rootAssembly.instances['Core-1'].edges.getSequenceFromMask(
        {'[#1 ]', }, ), name='s-Set-Yneg', vertices=
    mymodel.rootAssembly.instances['Face sheet-1'].vertices.getSequenceFromMask(
        mask=('[#1 ]', ), )+)
)mymodel.rootAssembly.instances['Face sheet-2'].vertices.getSequenceFromMask(
    mask=('[#1 ]', ), ))
)mymodel.rootAssembly.Set(name='Middle', nodes=
    mymodel.rootAssembly.instances['Core-1'].nodes.getByBoundingBox(
        xMin = (-1.0e-6), yMin = ((float(L)/2)-(float(mscy)*0.75)),
        xMax = (float(c)+(2*float(t))), yMax = ((float(L)/2)+(1.0e-6))),
    mymodel.rootAssembly.instances['Face sheet-1'].nodes.getByBoundingBox(
        xMin = (-1*float(t)), yMin = ((float(L)/2)-(float(mscy)*0.75)),
        xMax = 0.0, yMax = ((float(L)/2)+(1.0e-6))),
    mymodel.rootAssembly.instances['Face sheet-2'].nodes.getByBoundingBox(
        xMin = float(c), yMin = ((float(L)/2)-(float(mscy)*0.75)),
        xMax = (float(c)+float(t)), yMax = ((float(L)/2)+(1.0e-6))),)

# Set wires
mymodel.rootAssembly.WirePolyLine(mergeWire=OFF, meshable=OFF,
    points=((mymodel.rootAssembly.instances['Rigid-Yneg'].referencePoints[2],
        mymodel.rootAssembly.referencePoints[12]), ))
mymodel.rootAssembly.Set(edges=
    mymodel.rootAssembly.edges.getSequenceFromMask(('[#1 ]', ),
        name='Wire-1-Set-1'))
mymodel.rootAssembly.WirePolyLine(mergeWire=OFF, meshable=OFF,
#------------------------- BOUNDARY CONDITIONS -------------------------------

# Connector boundary conditions
mymodel.ConnectorSection(name='ConnSect-1', rotationalType=ROTATION, translationalType=CARTESIAN)
mymodel.sections['ConnSect-1'].setValue(behaviorOptions={
    ConnectorElasticity(behavior=RIGID, table=(), independentComponents=(), components=(1, 2)),
    ConnectorElasticity(table=((float(Kr),),), independentComponents=(), components=(6,())))
mymodel.rootAssembly.SectionAssignment(region=
    mymodel.rootAssembly.sets['Wire-1-Set-1'], sectionName='ConnSect-1')
mymodel.rootAssembly.SectionAssignment(region=
    mymodel.rootAssembly.sets['Wire-2-Set-1'], sectionName='ConnSect-1')

#------------------------- CONSTRAINTS ---------------------------------------

# Tie - CoreFacesheet
mymodel.Tie(adjust=ON, constraintEnforcement=SURFACE_TO_SURFACE, master=
    mymodel.rootAssembly.instances['Core-1'].surfaces['Surf-3 Left edge'],
    name='Constraint-1', positionToleranceMethod=COMPUTED, slave=
    mymodel.rootAssembly.instances['Face sheet-1'].surfaces['Surf-2 Xpos'],
    thickness=ON, tieRotations=OFF)

mymodel.Tie(adjust=ON, constraintEnforcement=SURFACE_TO_SURFACE, master=
    mymodel.rootAssembly.instances['Core-1'].surfaces['Surf-4 Right edge'],
    name='Constraint-2', positionToleranceMethod=COMPUTED, slave=
    mymodel.rootAssembly.instances['Face sheet-2'].surfaces['Surf-1 Xneg'],
    thickness=ON, tieRotations=OFF)

# Coupling RigidCoreFacesheet
mymodel.Coupling(controlPoint=
    mymodel.rootAssembly.instances['Rigid-Ypos'].sets['Set-1'],
    couplingType=KINEMATIC, influenceRadius=WHOLE_SURFACE, localCsys=None,
    name='Constraint-3', surface=
    mymodel.rootAssembly.sets['s-Set-Ypos'], u1=ON, u2=ON, ur3=ON)

mymodel.Coupling(controlPoint=
    mymodel.rootAssembly.instances['Rigid-Yneg'].sets['Set-1'],
    couplingType=KINEMATIC, influenceRadius=WHOLE_SURFACE, localCsys=None,
    name='Constraint-4', surface=
    mymodel.rootAssembly.sets['s-Set-Yneg'], u1=ON, u2=ON, ur3=ON)

# Connector boundary conditions
mymodel.ConnectorSection(name='ConnSect-1', rotationalType=ROTATION, translationalType=CARTESIAN)
mymodel.sections['ConnSect-1'].setValue(behaviorOptions={
    ConnectorElasticity(behavior=RIGID, table=(), independentComponents=(), components=(1, 2)),
    ConnectorElasticity(table=((float(Kr),),), independentComponents=(), components=(6,())))
mymodel.rootAssembly.SectionAssignment(region=
    mymodel.rootAssembly.sets['Wire-1-Set-1'], sectionName='ConnSect-1')
mymodel.rootAssembly.SectionAssignment(region=
    mymodel.rootAssembly.sets['Wire-2-Set-1'], sectionName='ConnSect-1')
# Step
```python
mymodel.BuckleStep(name='Buckling analysis', numEigen=int(SE),
    previous='Initial', vectors=int(SV))
mymodel.steps['Buckling analysis'].setValues(maxIterations=int(SI),
    numEigen=int(SE))
```

# Load
```python
mymodel.ConcentratedForce(cf2=-1.0, createStepName='Buckling analysis',
    distributionType=UNIFORM, field='', localCsys=None,
    name='Load-1', region=mymodel.rootAssembly.sets['BC RP Ypos'])
```

# Boundary condition hinge roller support
```python
mymodel.DisplacementBC(amplitude=UNSET, createStepName='Initial',
    distributionType=UNIFORM, fieldName='', localCsys=None,
    name='BC Yneg', region=mymodel.rootAssembly.sets['BC RP Yneg'],
    u1=SET, u2=SET, ur3=SET)
mymodel.DisplacementBC(amplitude=UNSET, createStepName='Initial',
    distributionType=UNIFORM, fieldName='', localCsys=None,
    name='BC Ypos', region=mymodel.rootAssembly.sets['BC RP Ypos'],
    u1=SET, u2=UNSET, ur3=SET)
```

# Job
```python
mdb.Job(atTime=None, contactPrint=OFF, description=''
    echoPrint=OFF, explicitPrecision=SINGLE, getMemoryFromAnalysis=True,
    historyPrint=OFF, memory=90, memoryUnits=PERCENTAGE, model=mymodel,
    modelPrint=OFF, name='GL_1+x1', nodalOutputPrecision=SINGLE,
    queue=None, scratch='', type=ANALYSIS, userSubroutine='',
    waitHours=0, waitMinutes=0)
```

# Adjust keywordsblock
```python
mymodel.keywordBlock.synchVersions(storeNodesAndElements=False)
mymodel.keywordBlock.insert(123, '\n*Node File, Global=Yes,Last Mode = 2\nU')
```

# Submit job
```python
mdb.jobs['GL_1+x1'].submit(consistencyChecking=OFF)
mdb.jobs['GL_1+x1'].waitForCompletion()
```
# -*- coding: mbcs -*-
from part import *
from material import *
from section import *
from assembly import *
from step import *
from interaction import *
from load import *
from mesh import *
from optimization import *
from job import *
from sketch import *
from visualization import *
from connectorBehavior import *

#----------- GEOMETRIC NONLINEAR IMPERFECTION INCLUDED ANALYSIS --------------
# Units: mm, N, N/mm2, Nmm/Rad
# Set work directory between parantheses equal to Abaqus work directory.
directory = 'D:/Documents/Abaqus Temp/'

#------------------ PARAMETERS CAN BE CHANGED -------------------------------
# Predefined model names are GFRP = ('GFRP08', 'GFRP15', 'GFRP30')
_modelname = 'GFRP30'

# GNL step, deformation controlled, and imperfection
_SIini = 0.005  # Step; initial increment
_SImin = 1e-05  # Step; minimum increment
_SImax = 0.02   # Step; maximum increment
_SINum = 150    # Step; maximum number of increments

_SRyposU2 = -30.0  # mm BC; Rigid-Ypos displacement (U2) in y-direction

_n1 = 0.3    # mm Imperfection first buckling mode (positive or negative)
_n2 = 0.9    # mm Imperfection second buckling mode (positive or negative)

# Geometry system
_L = 2639.0  # System length
_D = 899.0   # Depth system
_Kr = 2.25e08 # Nmm/Rad Rotational spring stiffness supports: Kr = M/Phi

# Core
_c = 150.0   # mm Thickness
_Ec = 30.0   # N/mm2 Modulus of elasticity
_vc = 0.33   # - Poisson ratio

# GL step
SE = 2    # - Step; number of requested eigenvalues
SV = 20   # - Step; number of vectors
SI = 150  # - Step; Maximum iterations

#------------------------- MODEL ---------------------------------------------
#-----------------------------------------------------------------------------
for x1 in GFRP:
    mymodel = mdb.Model(modelType=STANDARD_EXPLICIT, name='GNL_'+x1)
    if 'Model-1' in mdb.models: del mdb.models['Model-1']
    session.graphicsOptions.setValue(backgroundStyle=SOLID, backgroundColor='#FFFFFF')
    vp = session.viewports['Viewport: 1']
    vp.viewportAnnotationOptions.setValue(title=OFF, state=ON, legendFont='-*-verdana-medium-r-normal-*-*-140-*-*-*-*-*-*', stateFont='-*-verdana-medium-r-normal-*-*-140-*-*-*-*-*-*', annotations=ON, compass=OFF)

    # Face sheet parameters
    if x1 == 'GFRP08':
        t = 0.88  # mm Thickness
        Ef = 8932.0  # N/mm2 Modulus of elasticity
        vf = 0.37  # - Poisson ratio
        mscx = 15.0  # Mesh size x-direction
        mscy = 5.0  # Mesh size core y-direction = mesh size face sheet y-direction
    elif x1 == 'GFRP15':
        t = 1.5
        Ef = 5900.0
        vf = 0.1
        mscx = 15.0
        mscy = 7.5
    elif x1 == 'GFRP30':
        t = 2.91
        Ef = 6345.0
        vf = 0.27
        mscx = 15.0
        mscy = 10.0

#------------------------- PARTS ---------------------------------------------
#-----------------------------------------------------------------------------
#------------------------- Core ----------------------------------------------
# Part geometry
    mymodel.ConstrainedSketch(name='__profile__', sheetSize=200.0)
    mymodel.sketches['__profile__'].rectangle(point1=(0.0, 0.0),
                                           point2=(float(c)+float(t), float(L)))
    mymodel.Part(dimensionality=TWO_D_PLANAR, name='Core', type=DEFORMABLE_BODY)
    mymodel.parts['Core'].BaseShell(sketche=mymodel.sketches['__profile__'])
    del mymodel.sketches['__profile__']
# Surface
mymodel.parts['Core'].Surface(name='Surf-1 Top edge', sidelEdges=mymodel.parts['Core'].edges.getSequenceFromMask(('[#4 ]', ), ))

mymodel.parts['Core'].Surface(name='Surf-2 Bottom edge', sidelEdges=mymodel.parts['Core'].edges.getSequenceFromMask(('[#1 ]', ), ))

mymodel.parts['Core'].Surface(name='Surf-3 Left edge', sidelEdges=mymodel.parts['Core'].edges.getSequenceFromMask(('[#8 ]', ), ))

mymodel.parts['Core'].Surface(name='Surf-4 Right edge', sidelEdges=mymodel.parts['Core'].edges.getSequenceFromMask(('[#2 ]', ), ))

# Material
mymodel.Material(name='XPS-FL')
mymodel.materials['XPS-FL'].Elastic(table=((float(Ec), float(vc)), )]

# Section
mymodel.HomogeneousSolidSection(material='XPS-FL', name='Core', thickness=float(D))
mymodel.parts['Core'].Set(faces=
  mymodel.parts['Core'].faces.getSequenceFromMask(('[#1 ]', ), ), name='Set-1')

# Section Assignment
mymodel.parts['Core'].SectionAssignment(offset=0.0, offsetField='', offsetType=MIDDLE_SURFACE, region=
  mymodel.parts['Core'].sets['Set-1'], sectionName='Core', thicknessAssignment=FROM_SECTION)

# Mesh - Assign element type, Assign Mesh Controls, Seed part, Mesh part
mymodel.parts['Core'].setElementType(elemTypes=((ElemType(elemCode=CPS4, elemLibrary=STANDARD), ElemType(elemCode=CPS3, elemLibrary=STANDARD)),), regions=(
  mymodel.parts['Core'].faces.getSequenceFromMask(('[#1 ]', ), ), ))

mymodel.parts['Core'].setMeshControls(elemShape=QUAD, regions=
  mymodel.parts['Core'].faces.getSequenceFromMask(('[#1 ]', ), ), technique=STRUCTURED)

mymodel.parts['Core'].seedEdgeBySize(constraint=FINER, deviationFactor=0.1, edges=
  mymodel.parts['Core'].edges.getSequenceFromMask(('[#5 ]', ), ), size=float(mscx))

mymodel.parts['Core'].seedEdgeBySize(constraint=FINER, deviationFactor=0.1, edges=
  mymodel.parts['Core'].edges.getSequenceFromMask(('[#a ]', ), ), size=float(mscy))

mymodel.parts['Core'].generateMesh()

# Automatic generated set from mesh
mymodel.parts['Core'].Set(name='Middle', nodes=
  mymodel.parts['Core'].nodes)
# Section Assignment

mymodel.parts['Face sheet'].Set(edges=mymodel.parts['Face sheet'].edges.getSequenceFromMask(('(#7 )',)), name='Set-1')
mymodel.parts['Face sheet'].SectionAssignment(offset=0.0, offsetField='', offsetType=MIDDLE_SURFACE, region=mymodel.parts['Face sheet'].sets['Set-1'], sectionName='Face sheet', thicknessAssignment=FROM_SECTION)

xMin = (-1.0e-6), yMin = ((float(l)/2)-(float(mscy)*0.75)),
xMax = (float(c)+(2*float(t))), yMax = ((float(l)/2)+(1.0e-6)))

# Part geometry

mymodel.ConstrainedSketch(name='__profile__', sheetSize=200.0)
mymodel.sketches['__profile__'].Line(point1=(0.0, 0.0), point2=(0.0, float(l)))
mymodel.sketches['__profile__'].VerticalConstraint(addUndoState=False, entity=mymodel.sketches['__profile__'].geometry[2])
mymodel.Part(dimensionality=TWO_D_PLANAR, name='Face sheet', type=DEFORMABLE_BODY)
mymodel.parts['Face sheet'].BaseWire(sketch=mymodel.sketches['__profile__'])
del mymodel.sketches['__profile__']

# Surface

mymodel.parts['Face sheet'].Surface(name='Surf-1 Xneg', side1Edges=mymodel.parts['Face sheet'].edges.getSequenceFromMask(('[#1 ]',)),)
mymodel.parts['Face sheet'].Surface(name='Surf-2 Xpos', side2Edges=mymodel.parts['Face sheet'].edges.getSequenceFromMask(('[#1 ]',)),)

# Surf-Yneg = Y negative according to global coordinate axisdirection
# Surf-Ypos = Y positive according to global coordinate axisdirection

# Set

mymodel.parts['Face sheet'].Set(name='Set-2 Yneg', vertices=mymodel.parts['Face sheet'].vertices.getSequenceFromMask(('[#1 ]',)),)
mymodel.parts['Face sheet'].Set(name='Set-3 Ypos', vertices=mymodel.parts['Face sheet'].vertices.getSequenceFromMask(('[#2 ]',)),)

# Material

mymodel.Material(name='GFRP-FL')
mymodel.materials['GFRP-FL'].Elastic(table=((float(Ef), float(vf))),)

# Section

mymodel.RectangularProfile(a=float(D), b=float(t), name='Profile-1')
mymodel.BeamSection(consistentMassMatrix=False, integration=DURING_ANALYSIS, material='GFRP-FL', name='Face sheet', poissonRatio=0.0, profile='Profile-1', temperatureVar=LINEAR)
# AssignBeamSectionOrientation (only applicable to wires)
    mymodel.parts['Face sheet'].assignBeamSectionOrientation(method=N1_COSINES, n1=(0.0, 0.0, -1.0), region=mymodel.parts['Face sheet'].sets['Set-1'])

# Mesh - Assign element type, Seed part, Mesh part
    mymodel.parts['Face sheet'].setElementType(elemTypes=(ElemType(elemCode=B23, elemLibrary=STANDARD), ), regions=(mymodel.parts['Face sheet'].edges.getSequenceFromMask(('[#1 ]', ')), ') ))
    mymodel.parts['Face sheet'].seedPart(deviationFactor=0.1, minSizeFactor=0.1, size=float(mscy))
    mymodel.parts['Face sheet'].generateMesh()

# Automatic generated set from mesh
    mymodel.parts['Face sheet'].Set(name='Middle', nodes=mymodel.parts['Face sheet'].nodes.getByBoundingBox(xMin=(-1.0e-6), yMin=((float(L)/2)-(float(mscy)*0.75)), xMax=(1.0e-6), yMax=((float(L)/2)+(1.0e-6))))

#------------------------- RIGID ---------------------------------------------
# Part geometry
    mymodel.ConstrainedSketch(name='__profile__', sheetSize=200.0)
    mymodel.sketches['__profile__'].rectangle(point1=(0.0, 0.0), point2=((float(t)*2)+float(c), 10.0))
    mymodel.Part(dimensionality=TWO_D_PLANAR, name='Rigid', type=ANALYTIC_RIGID_SURFACE)
    mymodel.parts['Rigid'].AnalyticRigidSurf2DPlanar(sketch=mymodel.sketches['__profile__'])
    del mymodel.sketches['__profile__']

# Reference Point
    mymodel.parts['Rigid'].ReferencePoint(point=mymodel.parts['Rigid'].InterestingPoint(mymodel.parts['Rigid'].edges[2], MIDDLE))

# Set
    mymodel.parts['Rigid'].Set(name='Set-1', referencePoints=(mymodel.parts['Rigid'].referencePoints[2], ))

# Surface
    mymodel.parts['Rigid'].Surface(name='Surf-1', side2Edges=mymodel.parts['Rigid'].edges.getSequenceFromMask(('[#4 ]', ', ))

#------------------------- ASSEMBLY ------------------------------------------
# Assembly - Instance
    mymodel.rootAssembly.DatumCsysByDefault(CARTESIAN)
    mymodel.rootAssembly.Instance(dependent=ON, name='Core-1', part=
mymodel.parts['Core'])
mymodel.rootAssembly.Instance(dependent=ON, name='Face sheet-1',
    part=mymodel.parts['Face sheet'])
mymodel.rootAssembly.Instance(dependent=ON, name='Face sheet-2',
    part=mymodel.parts['Face sheet'])
mymodel.rootAssembly.Instance(dependent=ON, name='Rigid-Ypos',
    part=mymodel.parts['Rigid'])
mymodel.rootAssembly.Instance(dependent=ON, name='Rigid-Yneg',
    part=mymodel.parts['Rigid'])

# Instance - Rotate and translate
mymodel.rootAssembly.translate(instanceList=('Core-1', ),
    vector=((float(t)/-2), 0.0, 0.0))
mymodel.rootAssembly.translate(instanceList=('Face sheet-1', ),
    vector=((float(t)/-2), 0.0, 0.0))
mymodel.rootAssembly.translate(instanceList=('Face sheet-2', ),
    vector=((float(c)+(float(t)/2)), 0.0, 0.0))
mymodel.rootAssembly.translate(instanceList=('Rigid-Ypos', ),
    vector=((float(t)*-1), -10.0, 0.0))
mymodel.rootAssembly.rotate(angle=180.0, axisDirection=(0.0, 0.0, 1.0), axisPoint=(0.0, 0.0, 0.0), instanceList=('Rigid-Ypos', ))
mymodel.rootAssembly.translate(instanceList=('Rigid-Ypos', ),
    vector=((float(c)+float(t)), (float(L)+10.0), 0.0))

# Feature
mymodel.rootAssembly.ReferencePoint(point=((float(c)/2), -100.0, 0.0))
mymodel.rootAssembly.features.changeKey(fromName='RP-1',
    toName='RP Yneg')
mymodel.rootAssembly.ReferencePoint(point=((float(c)/2), (float(L)+100.0), 0.0))
mymodel.rootAssembly.features.changeKey(fromName='RP-1',
    toName='RP Ypos')

# Set
mymodel.rootAssembly.Set(name='BC RP Yneg', referencePoints={
    mymodel.rootAssembly.referencePoints[12], })
mymodel.rootAssembly.Set(name='BC RP Ypos', referencePoints={
    mymodel.rootAssembly.referencePoints[13], })
mymodel.rootAssembly.Set(edges=  
mymodel.rootAssembly.instances['Core-1'].edges.getSequenceFromMask(  
    ('[4 ]', ), ), name='s-Set-Ypos', vertices=  
mymodel.rootAssembly.instances['Face sheet-1'].vertices.getSequenceFromMask(  
    mask=('[2 ]', ), )+

    mymodel.rootAssembly.instances['Face sheet-2'].vertices.getSequenceFromMask(  
    mask=('[2 ]', ), )
)mymodel.rootAssembly.Set(edges=  
mymodel.rootAssembly.instances['Core-1'].edges.getSequenceFromMask(  
    ('[1 ]', ), ), name='s-Set-Yneg', vertices=  
mymodel.rootAssembly.instances['Face sheet-1'].vertices.getSequenceFromMask(  
    mask=('[1 ]', ), )+

    mymodel.rootAssembly.instances['Face sheet-2'].vertices.getSequenceFromMask(  
    mask=('[1 ]', ), )
)mymodel.rootAssembly.Set(name='Middle', nodes=  
mymodel.rootAssembly.instances['Core-1'].nodes.getByBoundingBox(  
    mymodel.rootAssembly.instances['Core-1'].edges.getSequenceFromMask(  
    mask=('[1 ]', ), )
)mymodel.rootAssembly.instances['Core-1'].edges.getSequenceFromMask(  
    mask=('[1 ]', ), )
)mymodel.rootAssembly.instances['Core-1'].edges.getSequenceFromMask(  
    mask=('[1 ]', ), )
)mymodel.rootAssembly.instances['Core-1'].edges.getSequenceFromMask(  
    mask=('[1 ]', ), )
)mymodel.rootAssembly.instances['Core-1'].edges.getSequenceFromMask(  
    mask=('[1 ]', ), )
)mymodel.rootAssembly.instances['Core-1'].edges.getSequenceFromMask(  
    mask=('[1 ]', ), )
)mymodel.rootAssembly.instances['Core-1'].edges.getSequenceFromMask(  
    mask=('[1 ]', ), )
)mymodel.rootAssembly.instances['Core-1'].edges.getSequenceFromMask(  
    mask=('[1 ]', )
xMin = (-1.0e-6), yMin = ((float(L)/2)-(float(mscy)*0.75)),
xMax = (float(c)+(2*float(t))), yMax = ((float(L)/2)+(1.0e-6)))\mymodel.rootAssembly.instances['Face sheet-1'].nodes.getBoundingBox(
xMin = (-1*float(t)), yMin = ((float(L)/2)-(float(mscy)*0.75)),
xMax = 0.0, yMax = ((float(L)/2)+(1.0e-6)))\mymodel.rootAssembly.instances['Face sheet-2'].nodes.getBoundingBox(
xMin = float(c), yMin = ((float(L)/2)-(float(mscy)*0.75))
xMax = (float(c)+float(t)), yMax = ((float(L)/2)+(1.0e-6)))

# Set wires
mymodel.rootAssembly.WirePolyLine(mergeWire=OFF, meshable=OFF,
points=((mymodel.rootAssembly.instances['Rigid-Yneg'].referencePoints[2],
   mymodel.rootAssembly.referencePoints[12]), ))
mymodel.rootAssembly.Set(edges=,
mymodel.rootAssembly.edges.getSequenceFromMask('([#1 ]', ),
  ), name='Wire-1-Set-1')
mymodel.rootAssembly.WirePolyLine(mergeWire=OFF, meshable=OFF,
points=((mymodel.rootAssembly.instances['Rigid-Ypos'].referencePoints[2],
   mymodel.rootAssembly.referencePoints[13]), ))
mymodel.rootAssembly.Set(edges=
mymodel.rootAssembly.edges.getSequenceFromMask('([#1 ]', ),
  ), name='Wire-2-Set-1')

#------------------------- CONSTRAINTS ---------------------------------------
#------------------------- CONSTRAINTS ---------------------------------------

# Tie - CoreFacesheet
mymodel.Tie(adjust=ON, constraintEnforcement=SURFACE_TO_SURFACE,
    master=mymodel.rootAssembly.instances['Core-1'].surfaces['Surf-3 Left edge']
    , name='Constraint-1', positionToleranceMethod=COMPUTED, slave=
mymodel.rootAssembly.instances['Face sheet-1'].surfaces['Surf-2 Xpos']
    , thickness=ON, tieRotations=OFF)
mymodel.Tie(adjust=ON, constraintEnforcement=SURFACE_TO_SURFACE,
    master=mymodel.rootAssembly.instances['Core-1'].surfaces['Surf-4 Right edge']
    , name='Constraint-2', positionToleranceMethod=COMPUTED, slave=
mymodel.rootAssembly.instances['Face sheet-2'].surfaces['Surf-1 Xneg']
    , thickness=ON, tieRotations=OFF)

# Coupling RigidCoreFacesheet
mymodel.Coupling(controlPoint=
mymodel.rootAssembly.instances['Rigid-Ypos'].sets['Set-1'],
couplingType=KINEMATIC, influenceRadius=WHOLE_SURFACE, localCsyst=\None,
    names='Constraint-3', surface=,
mymodel.rootAssembly.sets['s-Set-Ypos'], u1=ON, u2=ON, ur3=ON)
mymodel.Coupling(controlPoint=
mymodel.rootAssembly.instances['Rigid-Yneg'].sets['Set-1'],
couplingType=KINEMATIC, influenceRadius=WHOLE_SURFACE, localCsyst=\None,
    names='Constraint-4', surface=,
mymodel.rootAssembly.sets['s-Set-Yneg'], u1=ON, u2=ON, ur3=ON)
# Connector boundary conditions
mymodel.ConnectorSection(name='ConnSect-1', rotationalType=ROTATION, translationalType=CARTESEIAN)
mymodel.sections['ConnSect-1'].setValues(behaviorOptions=(
    ConnectorElasticity(behavior=RIGID, table=(), independentComponents=(),
    components=(1, 2)), ConnectorElasticity(table=((float(Kr), ), ),
    independentComponents=(), components=(6, ))))
mymodel.rootAssembly.SectionAssignment(region=
    mymodel.rootAssembly.sets['Wire-1-Set-1'], sectionName='ConnSect-1')
mymodel.rootAssembly.sets['Wire-2-Set-1'], sectionName='ConnSect-1')

# Step
mymodel.StaticStep(initialInc=float(SIini), minInc=float(SImin), maxInc=float(SImax),
    maxNumInc=int(SInum), name='Deformation', nlgeom=ON, previous='Initial')

# Boundary condition hinge roller support, deformationcontrolled
mymodel.DisplacementBC(amplitude=UNSET, createStepName=
    'Deformation', distributionType=UNIFORM, fieldName='', localCsys=None, name=
    'BC Yneg', region=mymodel.rootAssembly.sets['BC RP Yneg'],
    ul=SET, u2=SET, ur3=SET)
mymodel.DisplacementBC(amplitude=UNSET, createStepName=
    'Deformation', distributionType=UNIFORM, fieldName='', localCsys=None, name=
    'BC Ypos', region=mymodel.rootAssembly.sets['BC RP Ypos'],
    ul=SET, u2=float(SRYposU2), ur3=SET)

# Job
myjob = mdb.Job(atTime=None, contactPrint=OFF, description='', echoPrint=OFF,
    explicitPrecision=SINGLE, getMemoryFromAnalysis=True, historyPrint=OFF,
    memory=90, memoryUnits=PERCENTAGE, model=mymodel, modelPrint=OFF, name=
    'GLN_'+str(x1), nodalOutputPrecision=SINGLE, queue=None, scratch=''
    , type=ANALYSIS, userSubroutine='', waitHours=0, waitMinutes=0)

# Keyword
# The commandline "synchVersions" must be inserted prior to the keyword line.
# The keyword line number must be changed manually.
for x2 in GFRP:
    if x2 == 'GFRP08':
        mymodel.keywordBlock.synchVersions(storeNodesAndElements=False)
        mymodel.keywordBlock.insert(105, keywordI)
    elif x2 == 'GFRP15':
        mymodel.keywordBlock.synchVersions(storeNodesAndElements=False)
        mymodel.keywordBlock.insert(105, keywordI)
    elif x2 == 'GFRP30':
        mymodel.keywordBlock.synchVersions(storeNodesAndElements=False)
mymodel.keywordBlock.insert(105, keywordI)

# History output
mymodel.HistoryOutputRequest(createStepName='Deformation',
name='H-Output-2', rebar=EXCLUDE, region=
   mymodel.rootAssembly.instances['Face sheet-2'].sets['Middle']
   , sectionPoints=DEFAULT, variables=('U1', ))
mymodel.HistoryOutputRequest(createStepName='Deformation',
name='H-Output-3', rebar=EXCLUDE, region=
   mymodel.rootAssembly.instances['BC RP Ypos']
   , sectionPoints=DEFAULT, variables=('RF2', 'U2', ))
mymodel.HistoryOutputRequest(createStepName='Deformation',
name='H-Output-4', rebar=EXCLUDE, region=
   mymodel.rootAssembly.instances['Face sheet-2'].sets['Middle']
   , sectionPoints=DEFAULT, variables=('S11', 'E11', 'UR3', ))

# Field output
mymodel.FieldOutputRequest(createStepName='Deformation', name='F-Output-2', rebar=EXCLUDE, region=
   mymodel.rootAssembly.sets['Middle'], sectionPoints=DEFAULT
   , variables=('S', 'E'))

# Submit job
myjob.submit(consistencyChecking=OFF)
myjob.waitForCompletion()

#-------------------------------------------------------------
#------------------------- RPY OUTPUT EXCEL ----------------------
#-------------------------------------------------------------

# Delete previous output
if 'U1_RF2' in session.xyDataObjects: del session.xyDataObjects['U1_RF2']
elif 'U1' in session.xyDataObjects: del session.xyDataObjects['U1']
elif 'U2' in session.xyDataObjects: del session.xyDataObjects['U2']
elif 'RF2' in session.xyDataObjects: del session.xyDataObjects['RF2']
elif '_temp_1' in session.xyDataObjects: del session.xyDataObjects['_temp_1']

# Open output database
mydir = directory+'GNL_ '+x1+'.odb'
o3 = session.openOdb(name=mydir)

# Set current viewport to U1
session.viewports['Viewport: 1'].setValues(displayedObject=o3)
session.viewports['Viewport: 1'].odbDisplay.display.setValues(plotState=(
    CONTOURS_ON_DEF, ))
session.viewports['Viewport: 1'].odbDisplay.setPrimaryVariable(
    variableLabel='U', outputPosition=NODAL, refinement=(COMPONENT, 'U1'), )

# The node number in 'NSET MIDDLE' has to be set manually
# Create XYdata from odb
myodb = session.odbs[mydir]
xy_result = session.XYDataFromHistory(name='U1', odb=myodb,
   outputVariableName='Spatial displacement: U1 PI: Face sheet-2 Node 133 in NSET')
MIDDLE',
steps=('Deformation', ), )
xy_result = session.XYDataFromHistory(name='U2', odb=myodb,
    outputVariableName='Spatial displacement: U2 PI: rootAssembly Node 2 in NSET BC RP Ypos',
    steps=('Deformation', ), )
xy_result = session.XYDataFromHistory(name='RF2', odb=myodb,
    outputVariableName='Reaction force: RF2 PI: rootAssembly Node 2 in NSET BC RP Ypos',
    steps=('Deformation', ), )

# Combine and save xy data (additional graph in postprocessor)
xy1 = session.xyDataObjects['U1']
xy2 = session.xyDataObjects['RF2']
xy3 = combine(xy1, xy2)
xy3.setValues(sourceDescription='combine("U1","RF2")')
tmpName = xy3.name
session.xyDataObjects.changeKey(tmpName, 'U1_RF2')

# Write to Excel
d00 = session.xyDataObjects['U1']
d01 = session.xyDataObjects['U2']
d02 = session.xyDataObjects['RF2']
myxls = directory+'GNL_'+x1+'_Output.xls'
session.writeXYReport(fileName=myxls, xyData=(
    d00, d01, d02 ))