F.E.M.-calculations on a polyester coach-body

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F.E.M.-calculations on a polyester coach-body

Dr.ir. L.H. Braak
Mak.Müh. M.E. Dukul

FWF-88.014  Feb. 1988

bij order of:  Eskana b.v.
Loonseweg 16
5527 AC Hapert, Holland
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Appendix A: Leguval W16
1. Introduction

Vekoma B.V., sited at Vlodrop, is a Dutch industry specialized in designing and manufacturing amusements-installations like giant-wheels, double loop cockscreeks, swinging turns, tornado's etc. For a new indoor train circuit polyester coaches for the train had to be made. A subcontractor, Eskana B.V. at Hapert (N.B.), who is familiar with the processing and handling of laminated plastic products, is asked for making these traincoaches.

Eskana B.V. has contracted the department of Mechanical Engineering of the University of Technology at Eindhoven for finite element calculations on parts of the train-coach body to get informations about the strength and stiffness of their coach concept.

In this report a survey is given of the modelling of the structure and the results are presented for different loading conditions.

We thank mr. R.B. Nahuijser (Eskana B.V.) and mr. C. Peters and P. Hulsen (Vekoma B.V.) for their valuable coöperation.
2. The construction

2.1 The coach

A train, to be used in an amusement ride, consists of four coaches. Each coach has a steel undercarriage with suspension; on these frame a polyester body is mounted; the seat capacity of each coach is four. Not all the coaches have the same shape, the first one has a longer frontpart and is more or less streamlined. For the calculations of strength and stiffness of a body, dimensions of a "short" coach are taken.

![Fig. 1. Arrangement of the train.](image)

The seats are assumed critical parts in the concept of the body although a major part of the load is transferred directly to the steel undercarriage. Special attention will be given to loads due to stepping in or out, acceleration or breaking and to loads forced by pulling on the guidebars on top of the seats.

2.2 The material

The body is made as a laminated polyester shell, with wallthicknesses of 6 to 8 mm. For these composite structure the following lay-up is used:
- one glass fiber weaving of 250 g/m²
- two glass fiber weavings of 450 g/m²
- a roving of 800 g/m²
- two glass fiber weavings of 450 g/m²
and a top layer.

The epoxy used is Leguval W16, made by Bayer (West Germany). In Appendix A some characteristics are given of this material.
In the calculations with the finite element program this material is taken as homogenous, isotropic and linear. Then Young's modulus and Poisson ratio can be defined. Based on 40% glass-content we take the following values:

\[ E = 9,000 \text{ N/mm}^2 \]
\[ \nu = 0.3 \]
\[ \sigma_n = 160 \text{ N/mm}^2 \text{ (normal stress)} \]
\[ \sigma_b = 200 \text{ N/mm}^2 \text{ (bending stress)} \]

2.3 The Finite Element program

Calculations are carried out with I-DEAS, a linear, static, finite element program of SDRC, IHIO; U.S.A. This program runs on a VAX 750 computer. The element used is a 8-node, isoparametric thin shell. Pre- and postprocessing of the model is done by means of SUPERTAB; MODEL SOLUTION is used for calculating displacements and stresses. SUPERTAB and MODEL SOLUTION are important parts of the I-DEAS program.
3. The floor

3.1 Modelling

For each passenger a small part of the floor is available. At entering the coach a maximum load will occur as the passenger stands on one foot on the horizontal section of his part of the floor. We assume that he places his foot in the middle of the available width. Due to symmetry only a half of the relevant construction has to be considered. The bodyforce is taken as 750 N, so a vertical load of 375 N works on each half of the floor.

In fig. 2 an indication is given of the part under consideration; fig. 3 shows the main dimensions of the computer model. The load is distributed over one element (34 x 40 mm). To study the influence of the position of the load three cases are calculated. In fig. 3 the line of action of the resultant force is indicated. The boundary conditions in the plane of symmetry are taken in accordance with the rules of symmetry; on the other edges all degrees of freedom are suppressed.

3.2 Results

In fig. 4 and 5 an impression is given of the displacement of the model. The maximum displacement occurs in the plane of symmetry and in the horizontal part of the floor. The side wall nearly shows any deformation. In the three loadcases the global distribution of the displacements is very much the same.

The Von Mises-stress is taken as the most relevant value to evaluate the stress situation in any point of the models. In fig. 6 and 7 the stress distribution is shown for loadcase 1 and 2. Here again the maximum stress appears in points lying in the plane of symmetry in the neighbourhood of the point of application of the vertical load.

In Table 1 the maximum values of displacement and Von Mises stresses are collected. The calculations were also carried out for a wall thickness t=6mm.
Table 1: Floor section, load 750 N; vertical.

<table>
<thead>
<tr>
<th>load case</th>
<th>Wallthickness 8 mm</th>
<th>Wallthickness 6 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>max. displ. mm</td>
<td>max. stress N/mm²</td>
</tr>
<tr>
<td>1</td>
<td>0.4</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>1.2</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>1.9</td>
<td>14.5</td>
</tr>
</tbody>
</table>
Fig. 4  Displacements (mm)

Load Case 2

Fig. 5  Displacements (mm)
Fig. 6. Lines of equal von Mises stress

Fig. 7. Lines of equal von Mises stress
4. The seat; frontside

At entering the coach, passengers could place their feet on the front edge of the seat. The most critical condition occurs when a passenger stands on one foot in the middle of the two seats.

We assume that the seat is totally fixed at the connection with the steel frame. We also do not allow any displacement or rotation between seat and side walls.

Again, due to symmetry, we study only a half of the seat front part. In fig. 9 the dimensions of the computermodel are given. The load is a vertical one with a magnitude of 375 N working on one element with sides 30 x 51 mm.

In fig. 10 and 11 displacements of the seat are shown. The point with maximum displacement lies in the plane of symmetry at the end of the curved front part of the seat, as could be aspected.

In fig. 12 and 13 the stress distribution in the top surface of the shell elements is shown. Each line represent a certain value of the Von Mises stress. The maximum stress is in the plane of symmetry at the end of the seat, near the clamped boundary.

In table 2 some numerical values are given.

Table 2:
Seat, frontside, load 750 N; vertical

<table>
<thead>
<tr>
<th>Wallthickness 8 mm</th>
<th>Wallthickness 6 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load case</td>
<td>max displ.</td>
</tr>
<tr>
<td>mm</td>
<td>mm</td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
</tr>
<tr>
<td>2</td>
<td>0.89</td>
</tr>
</tbody>
</table>

In loadcase 1 the force of 750 N was taken normal to the surface of the shell. The differences with the reported calculations, with a vertical loading of the surface, are very small. So for this case numerical values are not given.
Fig. 8. SECTION OF THE FRONT PART SEAT

Fig. 9. MAIN DIMENSIONS FRONT PART SEAT
Fig. 10. Displacements (mm)

Fig. 11. Displacements
Fig. 12 Lines of equal von Mises stress

Fig. 13 Lines of equal von Mises stress
5. The seat

5.1 Modelling

The seat is subjected to different loading conditions, due to accelerations of the train. The forces arise from the masses of the passengers. We calculate the loads in situations where two passengers, 75 kg each, are sitting on a seat. It is sufficient to take into account only one half of the seat, the other half is a symmetrical one.

In order to calculate the forces working on the seat or on the back, it is necessary to know the mass distribution of a human body. The figures used here are based on "Humanscale", "1/2/3" [1]. These tables give the following data:
- head and neck : 75 N
- trunk and arms : 450 N
- upperlegs : 150 N
- lower legs and feet : 90 N

A number of load cases is examined. In table 3 the most important parameters for these load cases are given.

Table 3: Load cases for the seat.

<table>
<thead>
<tr>
<th>load case</th>
<th>vertical</th>
<th>forward</th>
<th>sideways</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4 g</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1 g</td>
<td>- 1 g</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-</td>
<td>2 g</td>
</tr>
<tr>
<td>5</td>
<td>4 g</td>
<td>-</td>
<td>1 g</td>
</tr>
<tr>
<td>6</td>
<td>2 g</td>
<td>-</td>
<td>3 g</td>
</tr>
</tbody>
</table>

The loads on the seat are distributed over a number of elements as shown in fig.14.

In a normal sitting position the vertical load on the back of the seat is only 8% of the bodyforce. This part of the load is neglected. In loadcase 2 it is assumed that by acceleration of the train the mass of head and trunk makes a contact in the upper part of the back.

Load case 3 was a control load, with identical results as loadcase 1.

In loadcase 4, 50% of the weight of a neighbour is counted to the passengers
weight to simulate the leaning over of one person to the other as the train rides through a horizontal curve.

Loadcases 5 and 6 are combinations of herefore mentioned load situations.

**Boundary conditions**

In the midplane of the seat the boundary conditions are taken with respect to the symmetry of the construction. To limit the number of elements and to save computing time the outer sidewall is not modelled with elements. The outer edge of the horizontal parts (the railings) are taken as free edges. This simplification will lead to slightly larger deformations and higher stresses. Furthermore the seat is fixed at the steel under carriage. All the nodes of one row of elements do not have any degree of freedom.

5.2 Results

In fig. 15 and 16 global impressions are given of the deformation of the seat due to the specified loadings. Noticable are the loadcases 2 and 6. In case 2 bending of the back of the seat is the most important phenomenon. As a consequence the upperstructure, the U-shaped beam, is subjected to torsion. In case 6 the point of maximum deflection lies in the side wall. This deflection is about 50% greater then in loadcase 4 as could be aspected. The vertical load, even with accelerations of 4 g, does not lead to important deformations.

Stresses are shown in the colorplots fig. 17-22. For each plot a seperate scale is used. In loadcase 2 and 5 low values of the maximum von Mises stresses occur. The extreme value of these stresses appears in loadcase 6 in points of the inner sidewall. There is a smooth function for the stress over that plane; there are not strong gradients nor sharp peaks in the stress distribution.

In table 4 Relevant data are collected.
Table 4: Seat, (8 mm wall thickness)

<table>
<thead>
<tr>
<th>load case</th>
<th>max. displ. mm</th>
<th>max. stress N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.69</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>1.92</td>
<td>4.8</td>
</tr>
<tr>
<td>4</td>
<td>1.47</td>
<td>8.1</td>
</tr>
<tr>
<td>5</td>
<td>0.69</td>
<td>14.1</td>
</tr>
<tr>
<td>6</td>
<td>2.13</td>
<td>12.1</td>
</tr>
</tbody>
</table>
Fig. 14 LOADCASES for SEAT
LOADCASE 1  MAX DISPL: 0.69 mm

LOADCASE 2  MAX DISPL: 1.92 mm

Fig. 15  Displacements
Fig. 16 Displacements
6. Seat with coach railing

On top of the frontseats a steel coach railing is attached. This railing consists of thinwalled steel pipes which are bolted to the polyester structure. Steel plates on both sides of the polyester ensure a rigid connection between railing and seat.

The railing is modelled by means of straight beams. There is a rigid connection between nodal points positioned at the top of the seat and the nodal points of the steel plates positioned on the polyester. The beams which are welded to the steel plates are modelled in such a way that the end node of the beam coincides with a midnode of a shell element.

Three loadcases are examined, see fig.23. On the railing a horizontal force of 525 N is working. Extra forces on the back of the seat may be introduced.

From fig.24 it can be observed that the relative large displacement of points of the railing are caused by the twisting of the upper structure of the seat. The steel reinforcement plates may give a fairly good distribution of the pressure, but these plates have a small stiffness with respect to torsion.

The maximum stresses (fig.25) occur in the steel plates. These stresses, up to 100 N/mm², are still beneath the elastic limitstress. In the polyester parts the stresses reach to a much lower value: less then 15 N/mm², and are working only in the upperside of the seat.

In table 5 the results of the loads on the railings are shown.

**Table 5:**
Results of seat with railing.

<table>
<thead>
<tr>
<th>load case</th>
<th>Max. disp</th>
<th>Max. stress</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>polyester</td>
<td>steel</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>8.3</td>
<td>14.9</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>8.1</td>
<td>10.2</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>8.6</td>
<td>19.6</td>
<td>101</td>
<td></td>
</tr>
</tbody>
</table>

\[ F_x = -525 \text{N}; \quad R = 0 \]
\[ F_x = -525 \text{N}; \quad R = 265 \text{N} \]
\[ F_x = +525 \text{N}; \quad R = 265 \text{N} \]
7. Shearforce between coach and frame

Turning a horizontal curve causes a shearforce between the polyester coach and the steel frame. Also when the speed of the train is slowed down, shearing forces can occur.

We assume a fully loaded coach, having a weight of about 150 N; with four passengers, having a weight of 750 N each. If we take an acceleration of 1g the total force is 4500 N.

The connection between the coach and the frame is realized by means of 22 holes (40 mm) filled with polyester. The holes are drilled in the beams of the frame.

Assuming that each hole takes an equal amount of the load, the shear stress has a value of

\[
\tau = \frac{4500}{2 \times 11 \times \frac{1}{4} \cdot 40^2} = 0.2 \text{ N/mm}^2
\]

This value is negligible small.
8. Conclusions

A number of details are examined of a polyester coach for an amusement ride. Calculations are carried out with a finite element program. The modelling of the structure was fairly simple. Small corners and reinforcement ribs were omitted. Boundary conditions were taken in such a way that an overestimating of displacements and stresses should occur.

In all loadcases a very low value of the von Mises stress is calculated. This equivalent stress value is mainly influenced by the bending stresses in the elements used. Taking into account that only static analyses were carried out and multiplying the maximum stress values by a dynamic loadfactor, then again stress values do not reach the allowable value.

Furthermore, regions of maximum stress do not lie at corners or on sharp edges of the structure, so stress concentration factors are not relevant.

Due to the relative low value of the Youngs modulus the displacements, caused by extreme loading conditions, are counted in millimeters. Whether or not the computed stiffness of the structure is sufficient, is a question on which subjective appraisements play an important role.
Literature


Drawings
Vekoma : 86690-2-20
        : 86690-2-22
        : 86650-2-11
        : 86650-1-29
Leguval W 16

Leguval W 16 ist eine mittelviskose Lösung eines ungesättigten Polyesters in Styrol, die nach den üblichen Methoden warm oder kalt gehärtet werden kann. Es ist ein hochreaktives Harz.

Leguval W 16 zeichnet sich gegenüber den N-Typen durch erhöhte Wärmebeständigkeit aus.

Leguval W 16 ist ein Standardtyp mit vielseitigen Anwendungsmöglichkeiten. Er ist insbesondere für die Herstellung solcher Formteile zu empfehlen, die einer gewissen thermischen Belastung unterzogen werden, wo der Einsatz eines hochwärmebeständigen Harztyps jedoch noch nicht gerechtfertigt erscheint. Formteile dieser Art sind z. B. Boote, Rohre, Behälter, Karosserieteile, Profile, Knopfplatten u. a.

Leguval W 16 ist mit Styrol verträglich. Wegen der Verträglichkeit mit anderen Legual-Typen siehe Tabelle unter Ziffer 2.7.

Leguval W 16 zeigt bei Freibewitterung sehr gute Beständigkeit, neigt allerdings, sofern es nicht durch einen zusätzlichen Lichtstabilisator geschützt ist, zu einer geringen Vergilbung. Diese ist jedoch im allgemeinen ohne Einfluß auf die Gebrauchstüchtigkeit.

Leguval W 16 entspricht Typ 1130 nach DIN 16946.
Leguval W 16 ist im allgemeinen nicht für die Herstellung chemikalienbeanspruchter Telle vorgesehen. Unsere Angaben in der Tabelle „Chemikalienbeständigkei“ sollen nur einen allgemeinen Hinweis über die Beständigkeit gegen einige charakteristische Chemikalien geben. Sie sind aufgrund von Laboruntersuchungen an reinen Harzplatten (Gießplatten) während einer Einwirkungsdauer von 12 Monaten bei Raumtemperatur gemacht. Die Beurteilung erfolgte im Hinblick auf die technische Verwendbarkeit (verbliebene Biegefestigkeit); optische Veränderungen (Verfärbungen) wurden nicht in Betracht gezogen.
Leguval W 16

<table>
<thead>
<tr>
<th>Liquids</th>
<th>+</th>
<th>—</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wasser (dest. Wasser, Meer-, Mineralwasser)</td>
<td>+</td>
<td>—</td>
</tr>
<tr>
<td>Wein</td>
<td>+</td>
<td>—</td>
</tr>
<tr>
<td>Zitronensäurelösung, 10%ig</td>
<td>+</td>
<td>—</td>
</tr>
</tbody>
</table>

+: beständig  
—: unbeständig


Wir haben für die Messungen jeweils die Prüfmethoden benutzt, die uns am besten geeignet erschienen. Entsprechend mußten einige Felder der Tabelle frei bleiben. Messungen der Kugeldruckhärte und der Formbeständigkeit in der Wärme am Laminat sind oft nicht eindeutig, auch solche Werte sind deshalb nicht aufgeführt.

### Chemikalienbeständigkeit *)

| Chemikalienbeständigkeit | Aceton | Äthanol, 96%ig | Akkusäure | Amelensäure, 10%ig | Ammoniak, konz. | Ammoniak, 5%ig | Benzin (Normal, Super) | Benzol | Chlorkalklösung, 10%ig | Dieselkraftstoff | Essigsäure, konz. | Essigsäure, 10%ig | Formaldehydlösung, 30%ig | Glycol | Heizöl | Isopropylalkohol | Kochsalzlösung, alle Konz. | Maschinenöl | Methanol | Milchsäure, 10%ig | Natriumhypochloritlösung, 12%ig | Natronlauge, 20%ig | Natronlauge, 5%ig | Phosphorsäure, 85%ig | Phosphorsäure, 10%ig | Salpetersäure, konz. | Salpetersäure, 10%ig | Salzsäure, konz. | Salzsäure, 10%ig | Schwefelsäure, konz. | Schwefelsäure, 37,5%ig (= Akkusäure) | Schwefelsäure, 10%ig | Sodalösung, 10%ig | Tetrachlorkohlenstoff | Toluel | 1,2,2-Trifluor-Trichloräthan |
|-------------------------|--------|---------------|-----------|--------------------|-----------------|---------------|-------------------|-------|------------------------|-----------------|----------------|----------------|------------------------|-------|--------|----------------|------------------|-----------------|----------------|---------------|----------------|---------------------|----------------|---------------|-------------------|-------------------|-----------------|-----------------|----------------|-----------------|-----------------|---------------- |--------------------------|------------------|------------------------|-----------------|---------------------|----------------|-----------------|------------------|-------------------|

*) Angaben enthält das Produkt über eine Gruppe von Versuchen und Feinanalysen.
Mechanische und thermische Eigenschaften
im polymerisierten Zustand

Zugverhalten von Leguval W 16 in Abmischung
mit Leguval E 81 (DIN 53455)

Es bedeutet:
$\sigma_R$: Reißfestigkeit (Zugfestigkeit)
$\varepsilon_R$: Reißdehnung
$E$: Elastizitätsmodul
Mechanische und thermische Eigenschaften im polymerisierten Zustand *)

<table>
<thead>
<tr>
<th>Prüfnorm</th>
<th>Dimension</th>
<th>reines Harz</th>
<th>verstärkt mit</th>
<th>Glasseidenmatte</th>
<th>Glasseidengewebe 181</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>30 Gew.-%</td>
<td>40 Gew.-%</td>
<td>60 Gew.-%</td>
</tr>
<tr>
<td>Zugfestigkeit (= Reißfestigkeit)</td>
<td>DIN 53 455 ASTM D 638</td>
<td>kp/cm²</td>
<td>500</td>
<td>900</td>
<td>1800</td>
</tr>
<tr>
<td>Reißdehnung</td>
<td>DIN 53 455 ASTM D 638</td>
<td>%</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Biegefestigkeit</td>
<td>DIN 53 452 ASTM D 790</td>
<td>kp/cm²</td>
<td>1100</td>
<td>1500</td>
<td>2000</td>
</tr>
<tr>
<td>Druckversuch-Quetschgrenze</td>
<td>DIN 53 454</td>
<td>kp/cm²</td>
<td>1500</td>
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<td>-</td>
</tr>
<tr>
<td>Druckfestigkeit</td>
<td>DIN 53 454 ASTM D 695</td>
<td>kp/cm²</td>
<td>-</td>
<td>1400</td>
<td>1600</td>
</tr>
<tr>
<td>Elastizitätsmodul</td>
<td>DIN 53 457 ASTM D 790 ASTM D 838</td>
<td>kp/cm²</td>
<td>35 000</td>
<td>70 000</td>
<td>90 000</td>
</tr>
<tr>
<td>Schlagzähigkeit Normstab</td>
<td>DIN 53 453</td>
<td>cm · kp/cm²</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Normkleinstab</td>
<td>DIN 53 453</td>
<td>cm · kp/cm²</td>
<td>7</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Dynatstoffprobe¹)</td>
<td>DIN 53 453</td>
<td>cm · kp/cm²</td>
<td>3</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>Kugeldruckhärte H_D 80</td>
<td>DIN 53 456</td>
<td>kp/cm²</td>
<td>1 900</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Formbeständigkeit in der Wärme nach Martens</td>
<td>DIN 53 458</td>
<td>°C</td>
<td>70</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Formbeständigkeit in der Wärme nach ISO/R 75¹)</td>
<td>DIN 53 461</td>
<td>°C</td>
<td>105</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

¹) 0,3 mm dick
²) Verfahren A: Heat Distortion Temperature (ASTM D 648)
³) siehe Legende im Anschluß an Chemikalienbeständigkeit