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Advances in moment transferring dvw reinforced timber connections – Analysis and experimental verification, Part 1

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HIGHLIGHTS

• Rotational stiffness of two closely spaced connections (a compound connection) is the same as a single connection.
• Application in column-beam and splice connections opens new design frontiers in structural timber design.
• This reinforced timber connection behaves isotropic, i.e. no angle to grain dependency.

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ABSTRACT

Considerable advances in the moment transferring capacity of timber connections are achieved by using densified veneer wood reinforcement and expanded tube fasteners. This study focuses on the rotational stiffness of two dvw reinforced connections joined in series by a steel plate in a splice and column-beam type of connection. The study proves that, when certain conditions are fulfilled, two connections in series have the same rotational stiffness as one while the bending moment capacity increases. The analysis and test results are in excellent agreement and confirm the isotropic properties of this connection type.

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1. Introduction

It is generally known that timber connections are usually the weakest link in a timber structure. Using mechanical fasteners like screws, dowels, bolts and glued-in rods in a small connection area results in premature timber failure (splitting cracks, shear plugs, etc.) caused by interaction of localised stress concentrations. This occurs despite the fastener spacing distances that are supposed to prevent this interaction, Avent et al. [1], Jorissen [2]. Researchers have tried to improve the strength and stiffness of connections with traditional dowel-type fasteners by preventing crack formation and so fully utilizing the potential bearing strength of the timber. A generally recognised and successful method to reinforce the connection area is by gluing a reinforcement material onto the outer surface of the timber members Fig. 1. During the last two decades of the 20th century, many materials were tested for this purpose such as textile, glass-fibre, steel plates and plywood, Haller et al. [3], among others.

Considerable enhancement in strength and stiffness is achieved when steel plates are glued onto the timber surface leading to a significant improvement in the moment capacity, Leijten [4]. Steel, however, is not a suitable material to glue to wood. Not only is the bonding procedure laborious, also due to the discontinuity in stiffness of the two materials, high concentrated stresses are introduced at the bond line edges. As shown by Leijten [5] a high performance plywood type exists that does not have the disadvantages mentioned. It is the so-called dvw (densified veneer wood) which is manufactured under the trade name Lignostone®. Invented in the late 19th Century, the first scientific test reports date from around WWII when airplanes were produced using this material, Winter [6]. A summary of the physical and mechanical properties of dvw is presented in Kollmann [7], and Ehlbeck and Hättich [8]. For a timber connection with laterally loaded dowel-type fasteners, the embedment or bearing strength is a key parameter for the load-bearing capacity. For coniferous wood species the embedment strength is about 25 N/mm² for a wood density of 450 kg/m³, as stated in Eurocode 5 [9]. The embedment strength of dvw produced from cross-wise layered beech veneer plywood sheets is about 5–6 times higher, as reported by Kollmann [7] and Leijten [5]. Fig. 2 shows the relationship between embedment
strength and the specific density of dvw sheet material. Dvw with specified densities can be ordered in practice. The dvw used in this study has an approximate density of 1300 kg/m³.

The reinforcement allows an increase in the number of fasteners per unit area (reduced spacing) as crack initiation and propagation are prevented by the cross-layered structure and high strength of the product. The reinforcement also allows bigger diameter fasteners, although spacing reduction and fastener diameter depends on the type and properties of the reinforcement.

2. Moment connections in timber structures

In this study, the focus is on bending moment connections with laterally loaded dowel-type fasteners, which have a splice-type arrangement of the connecting members. The moment transferring connection with traditional dowel type fasteners belongs to the weakest of timber connections. For applications, where high moment capacity, rotational stiffness and ductility are required, dvw reinforcement and tube fasteners can be a viable solution as shown by this study. An example of a structure that often requires these features is a moment connection in a portal frame.

In the past, efforts to apply reinforcement materials in timber connections like glass-fibre, punched metal plates, steel plates and dvw were reported, Leijten [10]. The moment transferring capacity of non-reinforced moment connections with dowel-type fasteners does not usually exceed 10%–20% of the bending capacity of the timber members. The rotational stiffness of these connections is also very low compared to the timber member stiffness. However, the worst deficiency is the presence of hole clearance which results in slack bending moment take-up. The performance significantly increases when dvw-plates are bonded to the outer timber surfaces where the forces of the fastener are transferred. The strength of dvw lies between the strengths of timber and mild steel.

In the next section the fastener type is considered and the hole clearance problem is addressed.

2.1. Dowels versus hollow tubes

For moment connections, immediate load take-up is of significant importance, especially when the bending moment is reversed, due to wind forces for instance. To prevent undue deformations in the presence of hole clearance, a gap between the drilled hole and the fastener, should be avoided. The misalignment of the holes can cause these gaps, especially when the holes are inaccurately drilled in separately aligned members. This turns the application of tight fitting fasteners into something of a problem, and at the assembly stage, there are contradicting demands. Over-sized holes make assembly easy, but cause slack load-take. A solution was offered by Leijten [5] using expanded tube fasteners. For this purpose mild steel tubes with over-length are used. Over-length is defined as the tube length exceeding the total connection thickness. After the insertion of the tube that easily fits into oversized holes the expansion procedure increases the tube diameter until the clearance has disappeared, Fig. 3. After expansion, the hole diameter in the timber is a few millimetres bigger than the initial pre-drilled diameter so the timber is left slightly pre-stressed.

This pre-stress has no benefit, however, as it will disappear quickly due to the stress relaxation of the timber. In the drilled hole of the dvw reinforcement no clearance is left either, but the diameter increase is much less as the stiffness properties of dvw are higher. This expansion is achieved by using special shaped dies. Firstly, the tube ends are flared. Secondly, with the tube ends tightly gripped in the dies, the hydraulic jack continues to push and pull both dies towards each other until the flared ends are anchored in the washers, Figs. 3 and 4.

A steel rod, inserted through the hollow centre of the tube, ties together the two dies on either side of the connection and prevents inwards buckling of the tube wall. For this reason the tube can only increase in diameter. The biggest tube diameter used in this process is 33.7 mm with a wall thickness of 3.25 mm. The washer has multiple purposes. First of all it prevents the dies from damaging the timber surface around the hole. Secondly, as it is being pressed into the wood by the dies, the washer triggers an acoustic noise (cracks) which signals the termination of the expansion procedure. Thirdly, it anchors the tube ends. When large shear deformation occurs the tube will deform into an S-shape and because the washer prevents the tube ends being pulled inwards axial forces in the tube develop which contribute to the load-carrying capacity. This is known as the chord action. Naturally, insufficient diameter expansion of the tube affects the connection stiffness. It was expected that, by relating the over-length of the tube to the total thickness of the connection, the expansion could be controlled. This over-length was assessed by trial and error. Leijten [5] proposed that an over-length of 10% of the total connection thickness,
including the timber and dvw, would suffice. Recently, more detailed research into this topic revealed that an over-length of 15% is better but more than 18% is not advisable, as reported by Brandon [12]. In that situation, the tube ends directly under the dies start to buckle because the ends stick out too far and the tube forces the timber to split. Technical details regarding dimensions of the washers and the tubes are provided by Leijten [5].

In this study the dvw thickness is chosen so that the steel tube governs the deformation and strength of the connection. Due to the hollow nature of the tube it allows large amounts of plastic deformation are possible while splitting of the timber is prevented by the dvw. The dvw thickness allows spacing much closer to the loaded end and edges than with dowel type fasteners in non-reinforced connections. Leijten [5] has shown that, for the dvw thicknesses investigated, 3.5 times the tube diameter is the minimum.

Although high strength fibre materials have a tendency to be brittle, the ductile properties of dvw in compression are exceptional. Hardly any pinching of the hysteresis curves is observed when these connections are tested. The energy absorption during cyclic loads is impressive, making the connection well-suited for application in earthquake-prone areas, Leijten et al. [11]. Engineers who are introduced to this connection type are inclined to insert a solid bolt into the expanded tube, imagining that it will enhance the structural properties. However, this should be highly discouraged as in this case ductility no longer relies on the plastic deformation of the tube, but more on the bearing capacity and embedment deformation of the dvw. Since the latter is much less than the plastic deformability of the hollow steel tube, this action impairs the ductility of the connection. Another effect is increased pinching during cyclic load tests because elongated holes develop in the dvw during subsequent load cycles. To improve the performance it would be better to increase the tube wall thickness. This is achieved by using a one size smaller steel tube which is inserted and expanded inside the larger size. Leijten [5] showed that this will increase the strength by approximately 20%. The procedure is as follows: A 33.7 mm diameter tube with 3.25 mm wall thickness is expanded to fit a 35 mm diameter hole. The internal diameter will become about 28.5 mm which is a suitable diameter to hold an expanded second tube of 26.9 mm outer diameter. However, due to the expansion, the tube centre will probably not be perfectly cylindrical any more. Therefore, a 28.5 mm diameter drill is used to mill at least a cylindrical hole of 28.5 mm diameter. Furthermore, experiments by Leijten [5] showed that the dvw transforms the orthotropic non-reinforced connection into an isotropic connection which means that the influence of load to grain angle disappears. This property makes structural design calculations considerable easier, particularly for moment transferring connections.

2.2. Steel plates

One drawback of this build-up type of connection is the total thickness. If the connection members consist of glued laminated members the total connection thickness can easily exceed 500 mm, Fig. 5. This occurs when multiple members have to be joined as occurs in trusses where diagonal and vertical members join at the nodes. This situation should be prevented as it leads to undesired eccentricities. To reduce the thickness of the assembled members some of the timber members might be replaced by steel plate members, Fig. 6. The figure shows an assembly stage of a timber truss but with steel diagonals. Tests with three member connections, with 8 mm thick steel side plates, were conducted by Monné [13]. He showed that neither strength nor ductility was significantly affected by the use of steel plates replacing the timber members. Hence it is of interest to investigate a steel plate as a middle member as shown in Fig. 7.
The steel plate is fixed with four fasteners to the vertical members and connected with the same number of fasteners to the other horizontal members to form, in this case, a beam-to-column connection. The dvw is glued to all timber members separately. During assembly, the layout of the holes in the steel plate ensures a narrow gap between the bonded dvw sheets of column and beam. This small gap is required for easy assembly. A bending moment will change the inner angle of the beam and column. Dependent on the size of the initial gap, the dvw of both members will make direct contact. Unlike similar contacts in non-reinforced connections, this affects the behaviour considerably since the in-plane dvw compressive strength and stiffness are significantly higher than those of timber.

The two connections of Fig. 7 can be regarded as two separate connections as long as the dvw of both connections does not make physical contact. When both closely-spaced connections are considered as one (compound) connection, the rotational stiffness is normally 50% the rotational stiffness of a single connection as they act in series, Fig. 8. When the gap between the dvw closes (gap closure), however, a new situation occurs and one might question if the combined rotational stiffness is still reduced by 50%. In this respect a comprehensive study by Brandon [12] was carried out and details are presented below.

The main objectives of the study were to compare the moment transmission performance of both the single connection and the double (compound) connection with an internal steel plate, Fig. 8, as well as the difference between the design as splice and beam-to-column connection, Fig. 9. For clarity the shear and normal forces are left out. These issues are studied by using analytical, numerical and experimental methods of analyses. In the analytical study it is assumed that the tube fails first and no other premature failure mechanisms occur. These failure mechanisms are assessed numerically and verified by additional experiments. One of the failure modes that may occur is delamination of the bond between the dvw and the timber. In the analysis of the stresses in the glue-line the type of adhesive used and thickness of the glue-line are important. To assess the governing failure mechanisms a numerical study was performed. However, the results of this comprehensive part of the research will be published as a second paper.

3. The analytical study

The aim of the analytical study is to derive the moment–rotation relationship of a double (compound) connection with an internal steel plate. In this approach, a connection is considered with a rectangular dvw plate and four tube fasteners per plate, Fig. 9. The edge/end distance of each tube is 3.5 times the outer tube diameter, d. The connection is produced with four 18 mm diameter tubes located at edge and end distances from the sides of the square dvw area of 300 × 300 mm. The thickness of the timber members is not particularly relevant to the performance of the connection which is mainly governed by the dvw and the tubes. The theory discussed here is applicable to connections with other dimensions and, different numbers of tube fasteners. In the analytical study, it is assumed that the deformation of the connection is the same with or without a steel plate, Monné [13]. In the numerical study, the legitimacy of this assumption is tested. To describe the relationship between load and slip of one tube, the non-linear regression model given by Jaspart [14] is used and is as follows:

$$F = \frac{(a - b)\delta}{1 + \left(\frac{a - b}{b}ight)^2} + b\delta$$

(1)

where $\delta$ is the displacement or slip, mm; $F$ is the load per shear plane, kN; $a$ is the initial stiffness, kN/mm; $b$ is the strain hardening stiffness, kN/mm; $c$ is the pseudo-plastic resistance, kN/mm; $d$ is a curve parameter.

Leijten [5] found the values for the curve constants shown in Table 1 by fitting the curve on results of 20 test samples per tube diameter. The correlation between the test results and the defined curve is presented by the correlation coefficient ($R$) in the table. To proceed with the analytical analysis, the inverse of Eq. (1) is required for 18 mm tubes and 35 mm tubes. Since the inverse is difficult to derive analytically, a polynomial regression curve is derived. The value of $R^2$ is higher than 0.999 to ensure the resemblance with the inverse of Eq. (1) with the parameters of Table 1. The equations of the fitted curves are given by Eqs. (2) and (3). For the 18 mm diameter tube:

$$\delta = 9.387E - 07F^5 - 4.671E - 05F^4 + 7.522E - 04F^3 - 2.70E - 02F + 2.066E - 02$$

(2)

For the 35 mm diameter tube:

$$\delta = -1.809E - 10F^5 + 2.583E - 08F^4 + 1.955E - 07F^3 - 1.127E - 04F^2 + 7.977E - 02$$

(3)

Before gap closure of the dvw occurs Eqs. (2) and (3) allow the prediction of the moment rotation behaviour based on equilibrium of forces. Disregarding the influence of shear forces means that the
rotation centre of the deformation field coincides with the geometrical centre of the tubes. In most cases, however, shear forces cannot be ignored and this influence needs to be addressed. Shear forces cause the rotation centre of the deformation to move in the direction perpendicular to the shear force direction. The assessment of this position requires an iterative procedure because of the non-linear load deformation behaviour of the tubes. Given the situation before gap closure and that the bending moment and the shear load can be regarded as separate independent parameters, the moment rotation behaviour of the connection was assessed as presented in Fig. 10.

The figure shows that, as the shear force increases, the rotational stiffness of the connection is slightly enhanced up to shear forces of 150 kN. For higher shear forces the rotational stiffness slowly decreases. For shear forces higher than 270 kN the rotational capacity quickly decreases as the maximum load in one of the tubes is attained. A shear force/moment ratio higher than 150 kN/30 kNm for instance is, however, highly unlikely in conventional timber structures. For an example the reader is referred to Fig. 11. The two forces, $F_1$ and $F_2$, on the presented structure both correspond with a high bending moment of 30 kNm. The location of $F_1$ is, however, located close to the section of the column. Forces higher than 200 kN will in the case of this example have to be located above the column and therefore not be beared by the connection. The lower two curves of Fig. 10 therefore have an unrealistic ratio between the bending moment and shear force. From the analyses it can be concluded that the shear force hardly affects the rotational stiffness and moment capacity.

The same type of analysis is applied to the situation when the gap between the dvw of the connection members closes due to rotations. Also in that case, the rotation centre moves for every load step and an iterative procedure is required to locate the rotation centre which is still based on the equilibrium of forces. When the dvw in the beam-column connection makes contact, not only the dvw but also the timber members come into contact. In the splice joint, the end grain faces of both timber members make contact simultaneously with the dvw. Therefore, the compression stresses parallel to grain of both timber and dvw are activated and immediately contribute in the stress distribution. In the beam-to-column connection, however, the end grain faces of the timber member are not parallel and therefore only the stresses in the dvw are accounted for. The influence of the compressive stresses perpendicular to grain of the timber members can be neglected.
compared to the dvw although an effort is made to compensate for this effect. The analysis assumes linear-elastic timber behaviour. It is experimentally verified that dvw behaves linear-elastic full-plastic for in-plane compressive stresses, Fig. 12. Equations are derived to determine the contact height $h_c$ of the dvw, Fig. 13. The ratio of the linear-elastic part of the contact height and the full-plastic part is set by the parameter $\beta$.

As in practice there will always be an initial gap, which is defined as $t_g$. Because of imperfections and assembly requirements the analytical analyses are expanded to cover situations with an initial gap and without an initial gap, $t_g$. It is assumed that the value for the initial gap is equal on both side faces of the timber member so that contact between the dvw and timber on both sides of the steel plate occurs simultaneously.

Fig. 15 shows the symmetrical half of the connection, as well as the forces that occur, after the initial gap, $t_g$ is closed including the contact force, $F_c$. In this equilibrium method only the forces by the bending moment are considered. The aim is to get insight

![Fig. 12. Stress–strain relationship of dvw.](image1)

![Fig. 13. Gap closure with initial gap, $t_g$.](image2)

![Fig. 14. Influence of the parameter $\beta$.](image3)

![Fig. 15. Influence of the initial gap size $t_g$.](image4)

![Fig. 16. Results of analytic study of bending moment versus rotation for single and double (compound) connection.](image5)

![Fig. 17. Definition of rotational stiffness (ISO 6891 [15]).](image6)
into the influence of the initial gap on the load distribution. When the bending moment exceeds a certain value there will be contact pressure and the rotation centre will move downwards over a path as illustrated in Fig. 13. Again an iterative calculation procedure is used to locate the rotation centre. The height of the compressed contact surface is calculated by using the equilibrium of forces and geometrical requirements. If the results of both methods are similar, the location of the rotation centre is determined. The result of the analysis is shown by Fig. 14. It is based on a connection area of $300 \times 300$ mm and four 18 mm diameter tubes located near the corners. It is concluded that the influences of the parameter $\beta$, which represents the ratio between the linear-elastic part and the plastic part of the contact area, is negligible. Furthermore, the height of the contact area is small compared to the connection height of 300 mm. It appears that the compressive deformation of the dvw in the contact areas is, for all cases, smaller than 1 mm.

The influences of the initial gap $t_g$ on the moment–rotation behaviour is presented in Fig. 15. The steepest moment–rotation curve represents the absence of any gap. Subsequent curves show the influence of increasing gap values. The kink in the non-linear parts of the curves is caused by gap closure when dvw compressive stresses pick up. Current production practice in the Netherlands indicate that gaps are usually smaller than 4 mm and, as such, moment–rotation curves are expected to fall between the two curves on the furthest left. So although the influence of the initial gap on the bending moment versus rotation is substantial, accurate...
assembly, resulting in a small initial gap, will make it a non-issue. To summarize the most important conclusion of the analytical procedure, the use of an internal steel plate as shown in Fig. 7 does not lead to a stiffness reduction, provided the initial gap between the dvw is small. Fig. 16. This conclusion only holds if premature failure other than failure of the steel tubes is prevented.

4. Experimental work

The laboratory experiments focused on two types of connections, the column-beam connection and the splice connection, both of these consisting of two connections, Fig. 9. The purpose of the experiments was the verification of the analytical predictions. The thickness of the dvw sheets was 15 mm. The timber member depth and thickness were 300 mm and 60 mm, respectively. The wood species used was Norway Spruce (Picea abies). Since the dvw governs the structural performance, and thickness were 300 mm and 60 mm, respectively. The wood species used was Norway Spruce (Picea abies). Since the dvw governs the structural performance, the thickness of the timber members was chosen to prevent premature timber failure. A two-component polyurethane based adhesive, with an average measured shear strength of 9.3 MPa, was applied. The surfaces of both adherents were sanded in preparation for gluing. The average bond thickness achieved was 0.45 mm based on measuring the thickness before and after gluing. The over-length of the steel tubes, all with 18 mm diameter, was taken as 16%. The loading procedure followed the guidelines of ISO 6891 [15], which prescribes one load cycle between 10% and 40% of the estimated strength capacity before continuing the ramp load procedure. The maximum load or the occurrence of failure is achieved within 300±100 s. This test standard provides three stiffnesses: the initial stiffness $k_i$, modified stiffness $k_m$ and the elastic stiffness $k_e$, Fig. 17. The first $k_i$ is the tangent stiffness represented by a straight line in the moment-rotation curve, connecting two points on the moment-rotation curve; the origin and the start of the load cycle at 40% of the estimated bending moment. The modified stiffness $k_m$ is the average stiffness between 10% and 40% of the estimated bending moment capacity. The elastic stiffness $k_e$ is the average stiffness of the load cycle.

The number of experiments is low compared to the number usually required in timber research, the reason being that the behaviour is determined by the steel tubes and dvw, both of which have a much smaller standard deviation in mechanical properties than structural timber, Leijten [5].

Three beam-to-column tests and three splice connection tests were performed. The analysis shows the gap between the dvw sheets to be important and preferably as small as possible. Special attention given to the production of the test pieces could limit the gap to values smaller than 1.5 mm. During the experiments, the load was applied to close the inner angle between the timber members, Fig. 18. This closing mode is easy to achieve by pulling the timber members together using hydraulic jacks.

Non-reinforced moment transferring connections are usually weaker in the opening mode, as tensile perpendicular stresses occur. Leijten [5] has shown this is not an issue for the dvw reinforced connection. To prevent splitting failure at the load introduction area at the centre line of the timber members, 18 mm thick birch plywood sheets are glued onto the timber member surface. To gain adequate deformation, two hydraulic jacks were used both with 250 mm stroke length. The test pieces were laid down and tested on the laboratory floor. To prevent any interference by friction with the floor, the test pieces were positioned on rollers. For the splice connection, two 3 m long timber members were connected and loaded in a four point bending test, Fig. 19. The distance between the support centres was 4.8 m. The loading points were distributed equally at 1.6 m distance from the end supports. The rotational and translation deformations were measured at the connection centre to prevent unwanted timber deformation interfering with the results. For this purpose, three displacement transducers, A, B and C, were used on each side and carefully positioned, Fig. 20. Transducers A and B stood at right angles and measured the translation in their respective directions. Transducer C, located at 150 mm distance from B in combination with readings from B, determined the rotation. The transducers themselves were all attached to a sheet that was fixed close to the connection centre. A threaded steel rod with over-length was firmly attached with a nut to the steel plate centre and protruded on both sides. This rod brought the relative deformation and rotation to the outside, to be picked up by the transducers A, B and C. This method was earlier successfully applied by Leijten [5]. The readings from the transducers resulted in an accurate determination of the rotation centre movement

The detection of the rotation centre is important for verification of the analytical result. A few of the failure modes occurring during testing can be attributed to failure of the tubes, timber and bond line. One such typical failure was caused by the internal steel plate which cut through the tube in shear. One of the specimens failed prematurely due to inadequate bond capacity (test 90-2) and for that reason the test data was discarded. Inspection of the failed surface showed that an inadequate amount of adhesive had been applied. During loading of the first splice connection test (test 0-1) the absence of buckling constraints made the test specimen become laterally unstable which impaired proper data collection. For this reason the test results of this test was ignored as well. Fig. 21 shows the final loading stage of the splice and column-beam test specimens. It is clearly visible that the indentation of the horizontal beam member into the column member is very small, due to the dvw contact. The same applies for the splice specimen. At the final loading stage the vertical component of the compressive contact stress in the end grain face of the timber members in the splice connection cause a local crack without affecting the rotational or bending moment capacity.

Table 2

<table>
<thead>
<tr>
<th>Connection type</th>
<th>Rot. modified stiffness $k_i$ (kNm/rad)</th>
<th>Rot. tangent stiffness $k_t$ (kNm/rad)</th>
<th>Rot. elastic stiffness $k_e$ (kNm/rad)</th>
<th>Maximum bending moment (kNm)</th>
<th>Maximum rotation (rad)</th>
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<td>Column-beam 90-3</td>
<td>2649</td>
<td>3203</td>
<td>5408</td>
<td>41.16</td>
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<td>90-4</td>
<td>1138</td>
<td>1366</td>
<td>4080</td>
<td>38.86</td>
<td>0.1113</td>
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<td>2597</td>
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<td>7278</td>
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<td>6838</td>
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<td>2866</td>
<td>621</td>
<td>40.5</td>
<td>0.105</td>
</tr>
</tbody>
</table>

* Ignoring 90-4.
ness is split up into three values according to ISO 6891 [15], Fig. 17. Bear in mind that in Table 2 every line representing a splice or column-beam connection that consists of two individual connections has been combined within the data.

5. Discussion of the results

An overview of all valid experimental moment rotation curves are presented in Fig. 22. The curve with markers represents the moment–rotation curve derived analytically. The graph shows an acceptable agreement between the rotational stiffness predicted analytically and also measured in the experiments. Furthermore, there is also no clear difference between results of the splice and column-beam connection, indicating that the contribution of the compressive contact stresses in the dvw is significant in both connections. Only one experimental curve of specimen (90-4) was offset from the others, presumably caused by insufficient expansion of the tubes, as similar results have been attributed to this deficiency. Ignoring connection 90-4, the mean rotational stiffness value is in excellent agreement with the analytically derived rotational stiffness as shown in the two bottom lines of Table 2. This applies for both the modified and tangent rotational stiffness. The analytical method does not consider the enhanced stiffness after pre-loading and therefore this position in the table is void. It is observed that the maximum moment and rotational capacity showed little variation. When comparing the moment rotation curve with the one derived experimentally by Leijten [5] it is concluded that the steel plate enhances the moment capacity by about 10%.

6. Conclusion and outlook

The paper investigated whether the moment–rotation behaviour of two close spaced dvw connections with expanded tubes connected by a steel plate is significantly different to one single moment transferring connection. Therefor an analytical method was developed taking the load-slip behaviour of a connection with a single expanded tube as the starting point. For confirmation, experiments were conducted with two types of dvw connections with 18 mm diameter tubes, the so-called splice and column-beam connection. Based on the results, the following conclusions are drawn. The moment–rotation behaviour is not affected provided the dvw of the individual connections make contact at an early stage of loading. Positive agreement is found between the results of the analytical study and the experiments in terms of accurate prediction of the moment–rotation relationship and the maximum bending moment, as well as the linear and non-linear behaviour. This study confirms earlier observations that this connection type behaves isotropically, meaning that any load to grain angle of the fasteners can be ignored. Furthermore, the moment-rotational behaviour is always consistent and there is no significant difference between the behaviour of splice or beam-column connection.

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