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NUMERICAL INVESTIGATION OF THE STRUCTURAL BEHAVIOUR OF ADHESIVE FREE CONNECTIONS UTILISING MODIFIED WOOD

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ABSTRACT: An investigation was carried out to examine the potential to use modified wood as a replacement for metallic connections in timber structures. In recent years, there have been several studies examining the potential to utilise modified wood to improve the performance of engineered wood products. This study describes the development of finite element models validated against a series of experimental tests on spliced beam-beam timber connections. The spliced beams are formed using compressed wood (CW) dowels and slotted-in CW plates providing an all-timber solution. A parametric study is utilised to optimise the design of spliced beam-beam timber connections utilising CW plates and dowels. The parameters studied were dowel arrangement, plate length, plate thickness, beam width and depth. The results indicate that connections using CW dowels and plates can be successfully modelled using finite element (FE) software. An optimised design has been developed to improve stiffness and moment rotation capacity of the connection system.

KEYWORDS: Compressed Wood, Modified Wood, FE Modelling, Connections, Eurocode 5.

1 INTRODUCTION

In recent years, there has been a significant number of studies that have examined the benefits of using modified wood in structural applications [1–6]. The potential to use modified wood as a replacement for typical metallic connections using steel plates and steel fasteners was examined by Mehra et al. [7]. Mehra et al. [7] experimentally tested a series of spliced beam-beam connections utilising compressed wood (CW) material in the form of dowels and plates. The CW plates and dowels were manufactured using Scots Pine wood compressed in the radial direction with a compression ratio of approximately 54%. The final density of the compressed wood material ranged from 1100-1500 kg/m^3. The results demonstrated that the all-wood connections utilising modified wood could achieve approximately 80% of the load capacity achieved with comparable connections utilising steel components [7].

A finite element (FE) numerical model, capable of predicting the load-displacement behaviour of the adhesive free connections is developed and validated against the experimental results presented by Mehra et al. [7]. A parametric study is performed to evaluate the influence of beam geometry and the beams-beam splice configuration on the connection performance to develop an optimised connection system.

2 EXPERIMENTAL PROCEDURE

2.1 INTRODUCTION

The experimental tests on beams spliced at mid-span were performed at the National University of Ireland Galway in the Laboratory of the Timber Engineering Research Group (TERG). All tests were carried out under four-point bending in accordance with EN 408 [8]. As recommended by Wang et al. [9], a gap of 10 mm was used to avoid friction between the beams at mid-span and simple lateral supports were utilised to avoid lateral movement of the beams under load. This ensures that the connection was subject to a pure bending load. The load was applied at a rate of 0.15 mm/s to ensure each specimen failed within 300 ± 120s in accordance with EN 408 [8]. The vertical displacement was measured at the mid-span of each spliced beam. The experimental tests have allowed the flexural stiffness, rotational stiffness, maximum failure load and maximum bending moment of the connections to be determined (see Mehra et al. [7]). In this study, only the load-displacement behaviour is examined.

2.2 SPECIMEN MANUFACTURE

The timber used in this study was Irish-grown Douglas fir with a mean density of 477 kg/m^3. Each beam consisted of three laminates, 1575 mm in length and 52.5 mm thick. The cross-sectional area of each beam was 115 mm x 157.5 mm. All beams were conditioned at a temperature of 20 ± 2˚C temperature and 65 ± 5% relative humidity prior to testing. Each beam was routed at one end to accommodate slots for CW plates. Two plate depths were studied known as the "Full" plate and "Narrow" plate configurations as seen in Figure 1. Full plates extended the entire depth (157.5 mm) of the beam whereas narrow plates were positioned in the top and bottom 60 mm of the

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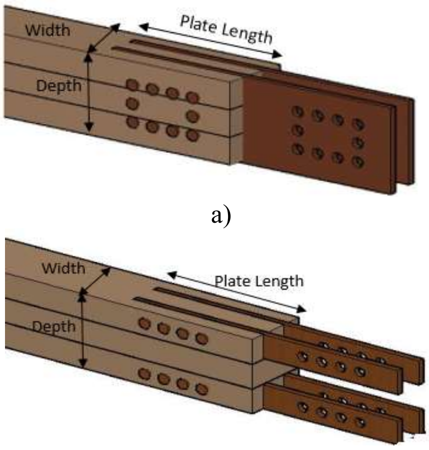
beams. The total length of the CW plates was 500 mm for both plate configurations.



a)

b)

***Figure 1:** AF Beam-beam connection configurations, a) full plate, b) narrow plate (4-dowel configuration)*

The full-depth CW plate configuration utilises ten 10 mm diameter CW dowels at mid-span and 2 CW plates in each beam. Two types of narrow-plate configuration were examined in which the number of dowels was varied. Three or four dowel configurations were used to connect each plate to each beam and a total of 4 CW plates were used in each beam. The dimension of the CW plates remained constant for both configurations so the 3-dowel configuration allows the spacing between the CW dowels to be increased.

3 NUMERICAL MODEL

A numerical model was developed using ABAQUS [10] Finite Element Analysis (FEA) software. For the numerical simulation, the timber beams, CW dowels and CW plates were modelled as orthotropic, linear elastic material in tension and linear elastic-perfectly-plastic materials in compression. Half symmetry was utilised as shown in Figure 2. The elements were modelled with 8-node hexahedron continuum elements with reduced integration and enhanced hourglass control (C3D8R). The sweep mesh algorithm was used to obtain a gradient in density in the mesh to provide greater refinement in the connection zone.

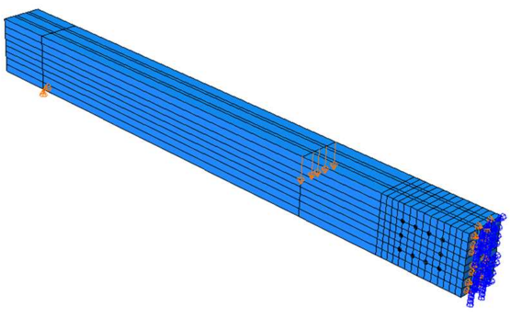


***Figure 2:** 3D finite element model of four-point bending tests using CW plates (Full plate configuration)*

In the zone around the holes, which were drilled to accommodate the CW dowels, reduced material properties were used. This is based on the foundation model proposed by Hong [11]. While Hong [11] reduces both stiffness and yield properties, the stiffness was not reduced in this study but the yield load was reduced by 50%. The material properties used in the model are presented in Table 1. The yield behaviour is based on the Hill yield criterion and has been validated against embedment tests in accordance with EN 383 [12] carried out in the parallel and perpendicular to the grain directions on both uncompressed and compressed wood.

Surface-to-surface contact with small sliding was used to model the interaction between the timber, CW plate and CW dowels. Hard contact was assumed, and a friction coefficient of 0.7 was used for the tangential friction force on the wood contact surfaces as presented by Hong [11].

***Table 1:** Timber properties*

Property		Timber	CW
Elastic Modulus (MPa)	E_L	11000	28000
	E_R	880	2240
	E_T	550	1400
Poisson's Ratio	ν_{LR}	0.48	0.48
	ν_{LT}	0.30	0.30
	ν_{RT}	0.56	0.35
Shear Modulus (MPa)	G_{RL}	786	2000
	G_{TL}	739	1880
	G_{RT}	79	200
Yield (MPa)	Parallel	22	130
	Perpendicular	10	80

A mesh refinement study was performed to improve the accuracy of the numerical result.

4 NUMERICAL RESULTS

4.1 INTRODUCTION

In this section, the numerical results are compared to the experimental beam-beam test results. To validate the numerical modelling approach, the numerical results are compared to the experimental results for three different configurations, namely the Full Plate, Narrow Plate - 3 Dowels, and Narrow Plate - 4 Dowels. The validated model of the Full Plate configuration is then used in a parametric study. The parametric study investigates the influence of beam depth, beam width, plate length, plate thickness and dowel arrangement on the structural response. To allow for easy assessment of the performance of different configurations, the results of the parametric study are examined and compared at a common mid-span vertical displacement of 40 mm. Additionally, the load at which the CW dowels and CW plate begin to yield is examined to determine the optimum design of the CW connection utilising adhesive free technology.

4.2 NUMERICAL VALIDATION

This section focuses on comparing the experimental results and the numerical results of the beam-beam connections with the full plate arrangement and the narrow plate arrangements with the 3 and 4 dowel configurations. The numerical longitudinal stress results for the full-plate beam-beam connection can be seen in Figure 3 at a displacement of 40 mm and the corresponding stress results for the CW plate and CW dowels can be seen in Figure 4a and Figure 4b, respectively.

It is important to note that this numerical model does not include brittle fracture or post-damage behaviour and as a result, the maximum experimentally observed load is overestimated. The post-failure behaviour requires further attention, however, the initial elastic behaviour and load-displacement behaviour up to the point of failure is well predicted and provide valuable information for optimising the connection geometry.

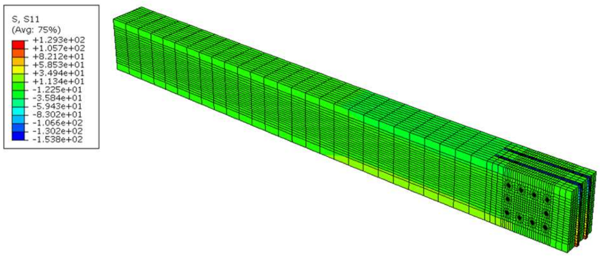


Figure 3: *The numerical model of beam-beam connection and longitudinal stress (S11) distribution*

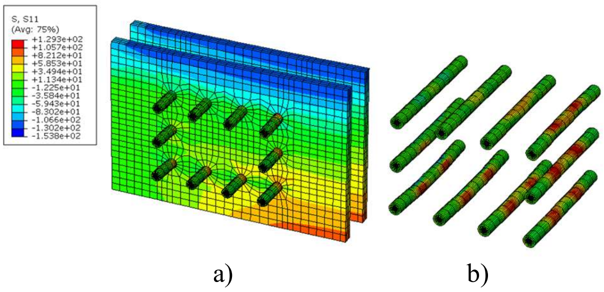


Figure 4: *The longitudinal stress (S11) distribution of, a) the CW plate and, b) CW dowels*

Figure 5 presents the experimental and numerically predicted load-midspan displacement behaviour for each design. Figure 5a shows the response of the full plate connection. The elastic behaviour and yield behaviour of the connection are well predicted. Figure 5b presents the load-displacement behaviour of beam-beam connections utilising narrow plates connected with 3 CW dowels. The initial elastic behaviour of the experimental beams are quite different and the FE model seems to agree well with the weaker of the two beams examined. Figure 5c shows the response of beam-beam connections utilising narrow plates connected with 4 CW dowels. When comparing Figure 5b and Figure 5c, it can be seen that there is a noticeable difference between the narrow plate beam-beam connections utilising 3 dowels and 4 dowels with increased stiffness observed in the beam-beam connections with 4 dowels. Due to the limited sample size, further experimental testing is required to determine if there is a statistically significant difference between these two configurations. Based on the limited number of specimens tested, the load-displacement behaviour is relatively well predicted by the numerical model.

The load-displacement behaviour from the numerical models of the different beam-beam connections is presented in Figure 6. It can be seen that the behaviour is quite similar for all beam configurations. The beam-beam connection utilising the full plate and the connection utilising narrow plates with 4 dowels demonstrated a similar initial elastic stiffness response and the beam-beam connection utilising narrow plates with 3 dowels demonstrates a marginally lower initial elastic stiffness response.

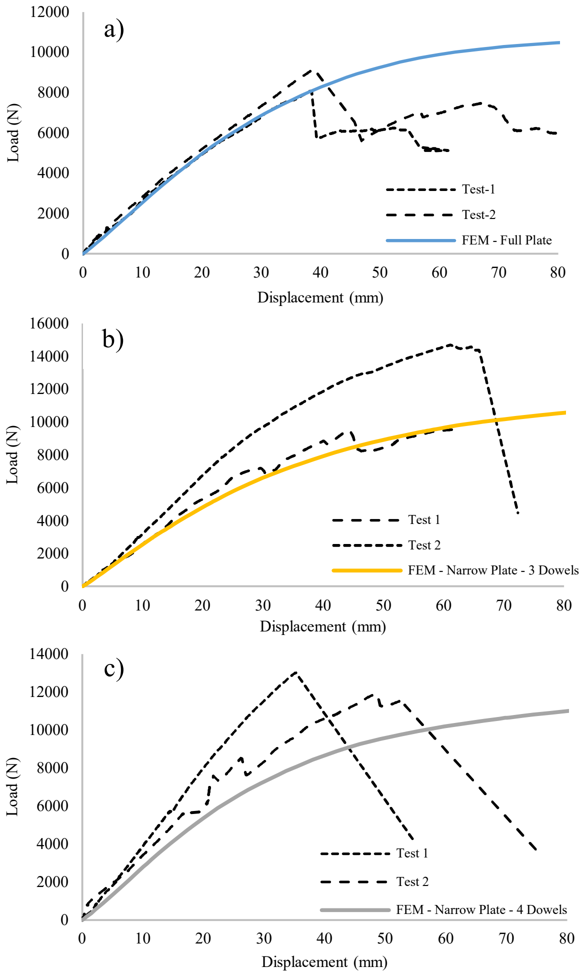


Figure 5: *Load-displacement behaviour for each connection configuration, a) Full plate, b) narrow plate - 3 dowels and c) narrow plate - 4 dowels*

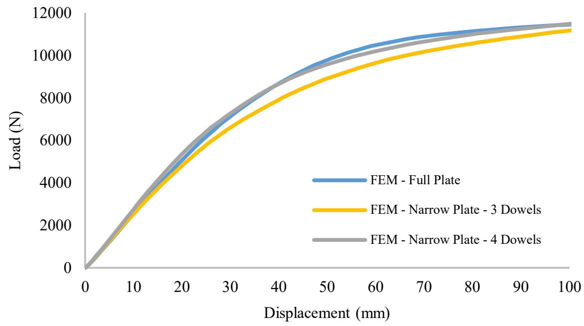


Figure 6: *Comparison of the load-displacement behaviour for each connection configuration from numerical models*

4.3 PARAMETRIC STUDY

This parametric study focuses on the full-plate configuration only. The initiation of yield within the CW plate and CW dowels was also studied with a view to refining the design and the load-displacement behaviour beyond the failure point is presented to examine the potential load-carrying capacity for a refined and optimised connection.

The influence of the beam depth on the load-displacement behaviour is presented for the full plate spliced beam-beams connection in Figure 7. Beam depths of 140 mm, 157.5 mm and 170 mm were examined. As expected, the depth of the beam can be seen to have a significant influence on the behaviour. By increasing the depth, the stiffness of the beam and ultimate load increases. At a common vertical displacement of 40 mm, the 170 mm beam achieved a load of 9.89 kN. This is 19.6% larger than the load achieved by a beam with a depth 157.5 mm (8.27 kN) and 36.8% larger than the load achieved by a beam with a depth 140 mm (7.23 kN).

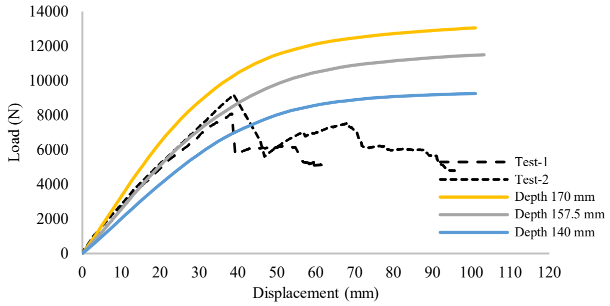


Figure 7: *Influence of beam depth on the load-displacement behaviour (tests performed on beam depth = 157.5mm)*

The load at which the different elements in the connection begin to yield was also examined. In the beam-beam connection with a depth of 140 mm, yielding initiated in the CW dowels at a relatively low load of 2.26 kN. In the same beam, the CW plate began to yield at a load of 5.38 kN. At a beam depth of 157.5 mm, the dowels and plate began to yield at loads of 5.91 kN and 9.51 kN, respectively. A 12.5% increase in depth resulted in a 161% increase in the load required to initiate yielding in the dowels. For the beam-beam connection with a depth of 170 mm, yielding initiated in the CW dowels at a load of 6.01 kN and the CW plate was found to yield at a load of 10.97 kN. Increasing the depth from 157.5 mm to 170 mm (7.9%) resulted in a 1.6% increase in the load required to initiate yielding in the dowels.

Figure 8 presents the influence of beam width on the load-displacement behaviour. It can be seen that the width of the beam has a slight effect on the initial stiffness of the connection and also increases the load at which yielding initiates. When increasing the width of the timber beam from 115 mm to 135 mm and then to 150 mm, the load required to achieve a displacement of 40 mm increased from 8.27 kN, to 9.49 kN and then to 9.90 kN.

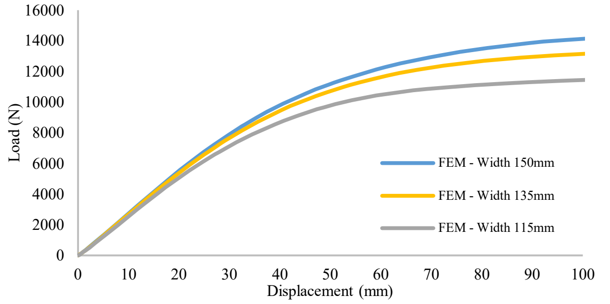


Figure 8: *Effect of beam width on the load-displacement behaviour (tests performed on beam width = 115mm)*

In the beam-beam connection with a width of 115 mm, the load required to initiate yielding in the dowels was 5.91 kN. Lower loads were achieved for the wider 135 mm (5.43 kN) wide and 150 mm (5.59 kN) wide beams. Wider elements require longer CW dowels and the embedment area is increased which causes a redistribution of the stresses within the connection resulting in yield stresses occurring at lower loads. This trend was not observed for the CW plates where the load required to initiate yielding increased with increasing beam width. The CW plate of the 115 mm, 135 mm and 150 mm wide beams began to yield at loads of 9.51 kN, 9.74 kN and 9.90 kN, respectively. It can be concluded that increasing the width of the timber beam results in delayed yielding of the plates but increased stresses in the CW dowels results in yielding at lower loads.

The effect of length and thickness of the CW plate on the load capacity and initial stiffness of the connections are presented in Figure 9 and Figure 10, respectively. In Figure 9, the results show that increasing the length of the plate from 500 mm to 600 mm increases the initial elastic stiffness. At a common displacement of 40 mm, the 500 mm plate configuration achieved a load of 8.27 kN while the 600 mm plate configuration achieved a load of 9.89 kN (19.6% increase). Increasing the plate length allowed the dowel spacing to be increased from 42 mm to 58 mm and is possibly responsible for the increase in stiffness and load-carrying capacity.

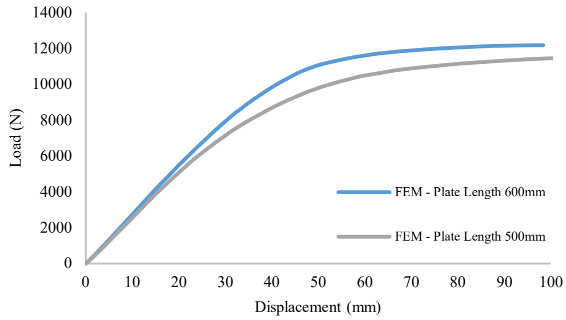


Figure 9: *Effect of CW plate length on the load-displacement behaviour (tests performed with plate length = 500mm)*

Increasing the plate length and dowel spacing delays the initiation of yielding significantly. In the beam-beam connection with a 500 mm long plate, yielding initiated in the CW dowels at a load of 5.91 kN. In the beam-beam connection with a 600 mm long plate, yielding initiated in the CW dowels at a load of 7.56 kN, a 27.9% increase. Finally, the CW plate in the 500 mm plate configuration began to yield at a load of 9.51 kN while the 600 mm plate configuration began to yield at a load of 10.61 kN. It can be concluded that increasing the length of the CW plate increases the stiffness and performance of the connection. Figure 10 presents the effect of plate thickness on the load-displacement behaviour of the beam-beam connections with the full-plate configuration. It can be seen that the stiffness of the connection improves with increasing plate thickness. At a common displacement of 40 mm, the 7 mm thick plate configuration achieves a load of 7.95 kN, the 10 mm thick plate configuration achieves a load of 8.27 kN and the 15 mm thick plate configuration achieves a load of 9.15 kN. Interestingly, increasing the plate thickness increases the initial elastic stiffness of the connection but also initiates yielding of the dowels earlier. In the beam-beam connection with 7 mm plates, yielding initiated in the CW dowels at a load of 5.79 kN. The CW dowels in the beam-beam connection with 10 mm thick plates did not begin to yield until 5.91 kN, however, the CW dowels in the 15 mm plate began to yield at just 5.52 kN. It can be concluded that increasing the thickness of the CW plate has a positive effect on the stiffness but also induces yielding of the CW dowels earlier in connections.

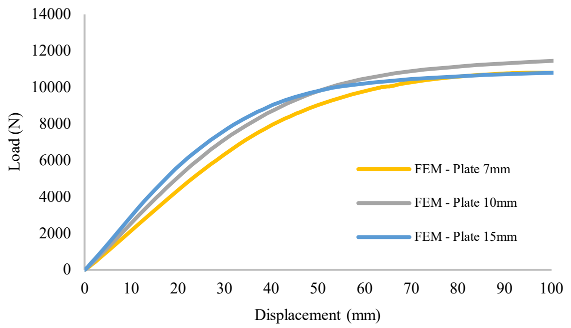
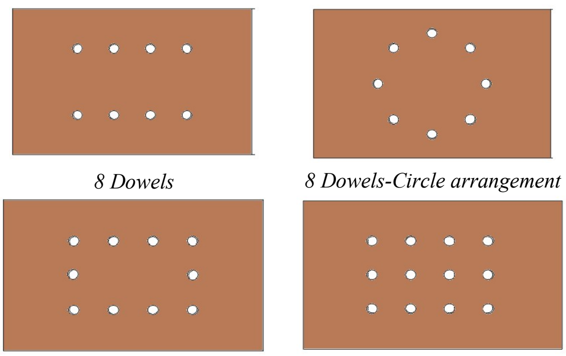


Figure 10: *Effect of CW plate thickness on the load-displacement behaviour (tests performed with plate thickness = 10mm)*

Various types of dowel arrangements for the full-plate configuration were selected for the parametric study as shown in Figure 11.



8 Dowels *8 Dowels-Circle arrangement*

10 Dowels *12 Dowels*

Figure 11: *Dowel arrangement of CW dowels in beam-beam connection using full-plates*

These configurations are the 8-dowel configuration in a square orientation, the 8-dowel configuration in a circular orientation, the 10-dowel configuration, and the 12-dowel configuration. Figure 12 presents the influence of dowel arrangement on the load-displacement behaviour.

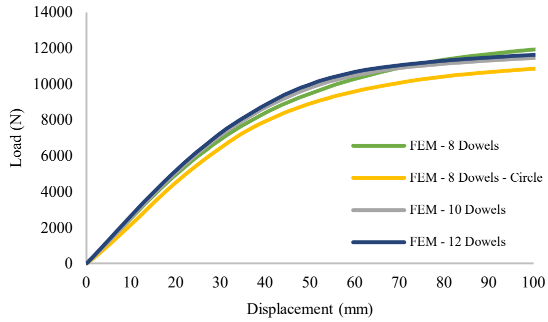


Figure 12: *Effect of number of dowels and dowel configuration on the load-displacement behaviour (tests performed with dowels configuration = 10 Dowels)*

The circular arrangement of 8 dowels results in a lower performance than that of the rectangular arrangement of 8 dowels. At a common displacement of 40 mm, the 8-dowel arrangement in a circular orientation achieved a load of 7.98 kN while the 8-dowel arrangement in a rectangular orientation achieved a load of 8.29 kN. The 10-dowel arrangement, which achieved a load of 8.27 kN did not show any improvement over the 8-dowel arrangement. This indicates that the addition of two extra dowels near the neutral axis of the beam (Figure 11- 10 Dowels) has an insignificant influence on the load-displacement behaviour. The 12-dowel arrangement was the stiffest of the configurations examined with a load of 8.94 kN at a displacement of 40 mm.
The results indicate that the rectangular orientation performed better than the circular orientation. In the beam-beam connection with 8 dowels in a circular orientation, yielding initiated in the CW dowels at a load of 3.99 kN while in the beam-beam connection with 8 dowels in a rectangular orientation, yielding only initiated at a load of 5.41 kN. A similar trend was observed for the CW plate with yielding occurring at a load of 8.26 kN and 9.78 kN for the circular and rectangular orientation, respectively. When focusing on the rectangular orientations, the load required to initiate yielding in the dowels increased with increasing numbers of dowels (8 dowels = 5.41 kN, 10 dowels = 5.91 kN and 12 dowels = 6.21 kN).

5 CONCLUSIONS

Finite element models of beam-beam connections using full-depth and narrow CW plates and CW dowels have been developed. These models were validated against test data from four-point bending tests presented by Mehra et al. [7]. The models were found to be good predictors of the behaviour up to peak load. Further development of the post-peak behaviour is required to capture the response to failure.

The validated modelling approach has been utilised to examine the influence of different connection parameters on the load-displacement behaviour of the full plate configuration with a view to refining the design. Additionally, the initiation of yielding of the CW dowels and CW plates has also been examined. Based on the obtained results from the parametric study, it was concluded that the most important parameters in beam-beam connections are the depth of the beam, length of CW plate and thickness of the CW plate. By increasing the depth, the stiffness of the beam and ultimate load increases and the yielding of the CW dowels and plates is delayed. To a smaller extent, increasing the width of the beam demonstrates a slight increase in the initial stiffness of the connection and increases the load at which yielding initiates. Increasing the plate length and by extension, the dowel spacing increases the stiffness and delays the initiation of yielding significantly. The CW plate thickness was shown to increase the initial elastic stiffness of the connection but also initiates yielding of the dowels at lower loads and requires further investigation.

The number and arrangement of dowels also require further investigation however it has been shown that the square orientation of dowels outperforms that of the circular orientation in terms of stiffness and delayed yielding of the connection components. Further numerical studies will investigate the influence of the different parameters on the narrow plate configuration.

ACKNOWLEDGEMENT

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