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Experimental study of cross-laminated timber wall panels

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Abstract The use of cross-laminated structural timber elements is becoming increasingly popular. The number of layers varies normally from three upwards. The structural performance of five-layer cross-laminated timber elements was investigated. The five layers consisted of 19 mm thick boards, laid successively at right angles to each other and glued together with PU-adhesive, layers 1, 3 and 5 lying in one direction and layers 2 and 4 in the other. The stiffness and strength of four cross-laminated timber elements (4955 mm long, 1250 mm wide and 96 mm thick) were studied during in-plane bending. Two of the elements were first partitioned into two parts that were reconnected in two different ways prior to testing. The influence of the way in which the cross-laminated timber elements were reconnected was studied, the behaviour observed being compared with the test results for the unpartitioned specimens with respect to both strength and stiffness. The experimental tests performed showed the cross-laminated timber elements to possess a high degree of stiffness and strength. There was also found to be a marked difference in behaviour between the two different ways in which the elements were connected to each other. One of the two connecting methods studied, being of less good design but earlier frequently used in Sweden, showed as expected poor structural performance, whereas the other one applied as a safer alternative performed well.

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Experimentelle Untersuchung von Wandelementen aus Brettsperrholz

Zusammenfassung Die Verwendung von Brettsperrholzbauteilen aus drei oder mehr Lagen gewinnt zunehmend an Beliebtheit. Das Trag- und Verformungsverhalten von fünflagigen Brettsperrholzelementen wurde untersucht. Die fünf Lagen bestanden aus 19 mm dicken, kreuzweise mit PU-Klebstoff verklebten Platten, wobei Lagen 1, 3 und 5 in eine Richtung und Lagen 2 und 4 in die andere Richtung orientiert waren. Die Biegesteifigkeit und -festigkeit in Plattenebene von vier Brettsperrholzelementen (4955 mm lang, 1250 mm breit und 96 mm dick) wurden untersucht. Zwei der Elemente wurden in Längsrichtung mittig aufgetrennt und dann vor der Prüfung auf zwei verschiedene Arten wieder miteinander verbunden. Untersucht wurde der Einfluss der Art der Verbindung der Brettsperrholzelemente auf die Festigkeit und Steifigkeit der Elemente durch Vergleich mit den Versuchsergebnissen der nicht geteilten Prüfkörper. Die Versuche ergaben, dass die Brettsperrholzelemente eine hohe Steifigkeit und Festigkeit aufwiesen. Es zeigte sich ein deutlicher Unterschied im Verhalten der zwei Arten der Wiederverbindung der beiden Elemente. Erwartungsgemäß ergab die weniger gute aber früher in Schweden oft verwendete Verbindungsart schlechte Ergebnisse, wohingegen die andere Verbindung, eine sicherere Alternative, gute Ergebnisse lieferte.

1 Introduction

Multi-storey timber-based structures have long been built in many different countries. Various challenges are connected with constructions of this type. One such challenge is that of stabilising the structure against horizontal wind loads. The most common stabilising system involves the use of a sheathing material such as OSB, plywood or gypsum, connected to the timber frame by nails or screws. Shear forces are thus transmitted by the connectors from the timber frame to the sheathing. The wall elements between separate stories are often connected by means of special brackets or some other form of hold-down devices. The design principles involved and the calculation methods employed have been dealt with extensively in the literature Källsner and Lam (1995), Kasal et al. (2004) and Ellis and Bougard (2001). In many cases, a stiffer wind bracing system of greater strength may be of interest, particularly in the case of narrow houses that are tall but have a relatively small foundation area. For houses in which the walls are perforated by door and window openings special structural design measures are often needed. In such buildings, the use of cross-laminated timber elements, either as parts of the walls or in the walls as a whole, can be of strong interest, a matter which has been studied for example by Dujic et al. (2004), Blass and Fellmoser (2004) and Moosbrugger et al. (2006). In heavily loaded parts of the walls, the connections between the cross-laminated wall panels are highly important for structural performance. The aim of the present study was to gain greater insight into the behaviour of structures of this type by investigating cross-laminated timber elements experimentally. Both the stiffness and strength of the elements and the ways of connecting the wall elements with each other were studied.

2 Tested specimens

Four wall elements of cross-laminated timber 4955 mm in length, 1250 mm in width and 96 mm thick were tested. The elements consisted of five layers of sawn boards, the successive layers being glued crosswise to each other. The fibres of the two outermost layers, 1 and 5, and of the middle layer, 3, extended in the direction of the length of the element, whereas layers 2 and 4 extended in the direction perpendicular to this, see Fig. 1. The 19 mm thick sawn boards of which these timber elements were composed were made of Norway spruce and were on the average about 120 mm in width. In the long direction, the boards were placed butt to butt with a random location of the butt joints, there being no finger joints connecting them. The boards were not strength graded but expected to be of class C24 or higher grade. The equilibrium moisture content of these elements was found to be about 13% at the time of testing. The highest and the lowest moisture-content values in a given board differed by about 2%. It is assumed that in the elements tested the variations in the material properties due to differences in moisture content were negligible.

3 Testing of joints

After stiffness testing of the elements 1 and 2 at a low load level, these two cross-laminated timber elements were sawn into two parts. These parts were then reconnected by use

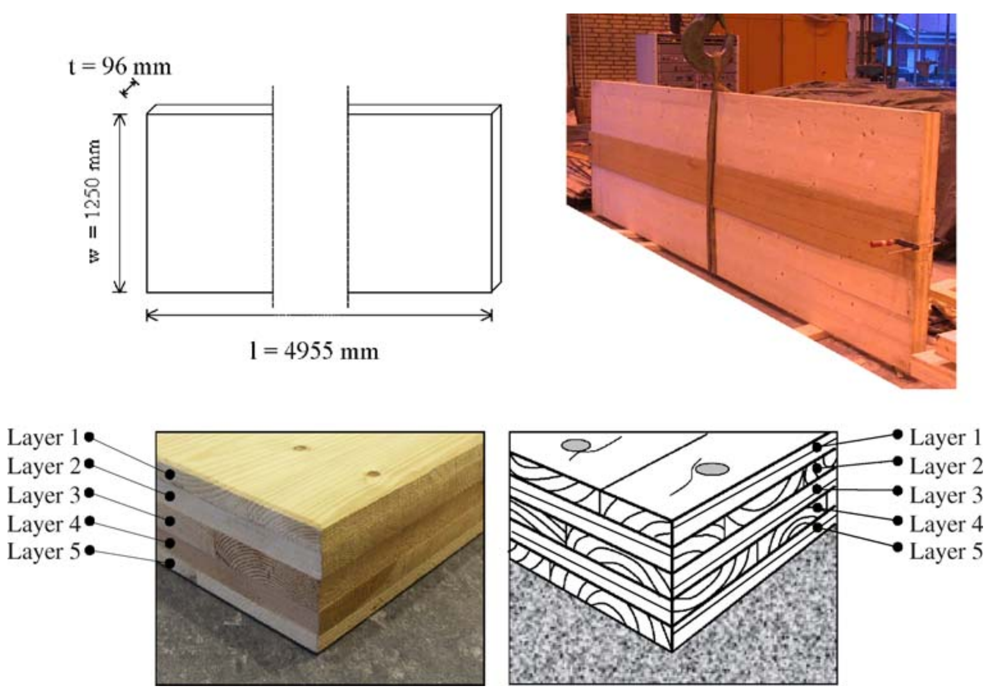

Fig. 1 The five-layer cross-laminated timber-wall elements tested
Abb. 1 Untersuchte Wandelemente aus fünflagigem Brettsperrholz

of two different jointing methods. The new wall elements having longitudinal joints were renamed as element 5 (made from element 1) and element 6 (made from element 2).

For element 5, a purely mechanical joint was employed. After this element had been partitioned, a 60 mm deep and 25 mm wide slot was cut into each of the two halves. A sawn board 120 mm wide, 25 mm thick and graded as C24 was fitted into the slot. Hexagonal-head wood screws, 96 mm long and 8 mm in diameter, were screwed both from the left and the right into the two sides of the element. This poor design, with the solid board and the hexagonal-head screws, of the joint was used in the experiment since similar joints have earlier been much used in practical design, although their capacity has never been verified experimentally. The screws were mounted in a row both from the first and the second side in predrilled holes as shown in Fig. 2a. By placing them in a single row like this the worst case was obtained from a shear force perspective.

For element 6 both gluing and screwing were used for the joint. A sheet of fibreboard of quality C40 (wet process fibreboard, HB.HLA2, Masonite AB) 300 mm wide and 8 mm thick was applied to both sides of the partitioned specimen, see Fig. 2b. The adhesive used was a single-component polyurethane with a curing time of approximately 12 h. In addition the sheets of fibreboard were also fastened mechanically by means of 50 mm long hexagonal-head wood screws 6 mm in diameter located in two parallel rows, as shown in Fig. 2b. The distributed normal forces from the screws resulted in a proper gluing pressure.

4 Tests of stiffness and strength

An overview of the tests performed for the wall elements numbered 1 to 6 are given in Table 1. A schematic diagram of the testing setup is presented in Fig. 3. The loading in the vertical plane of a simply supported cross-laminated timber element, acting as a horizontal beam, is similar to the loading of a cantilever wall element of half the length fixed to the ground.

The elements 1 to 4 were first loaded in a non-destructive way at a low loading level in order to determine their initial stiffness. Each of the elements was loaded by the testing machine, see Fig. 4, under displacement control to a load of 200 kN and was then unloaded. The crosshead

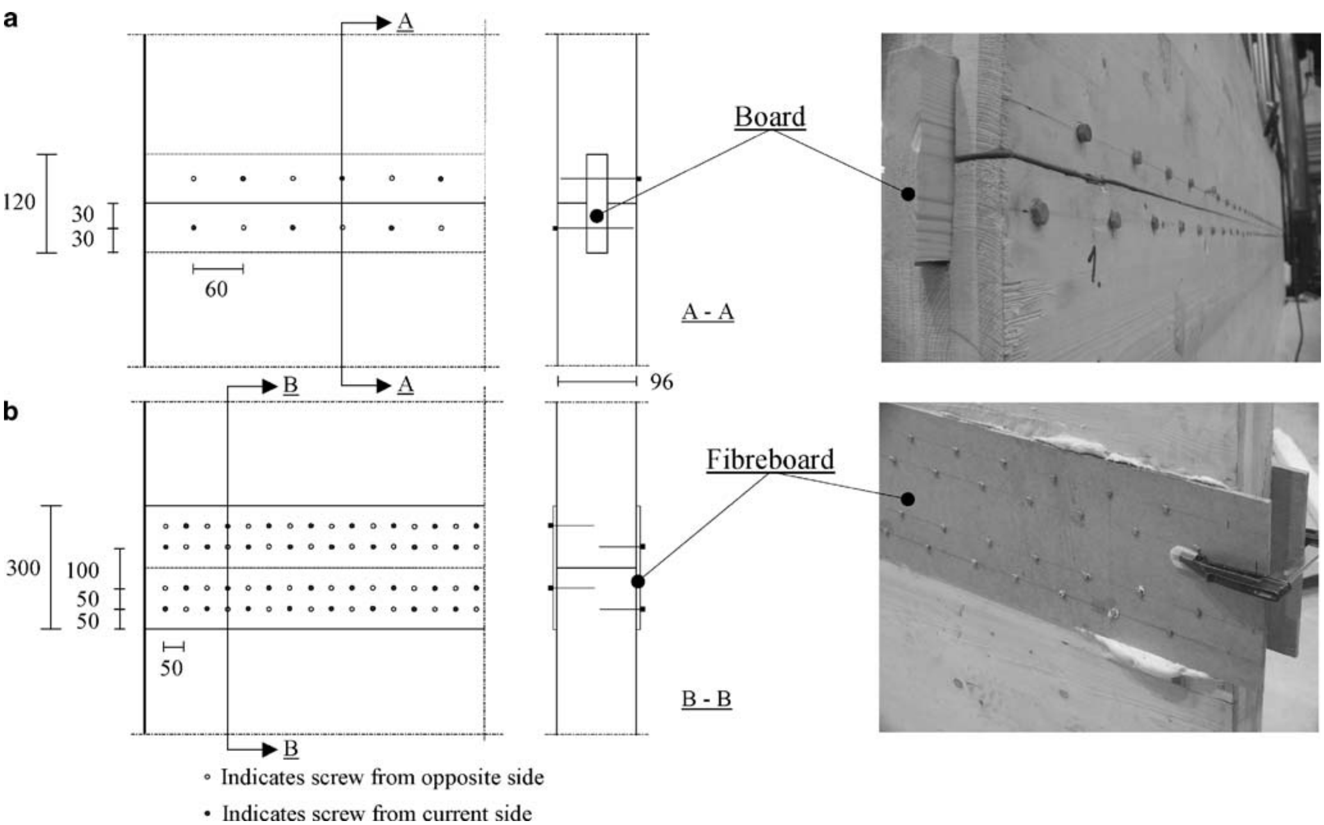

Fig. 2 Joints of the longitudinal wall-elements: (**a**) element 5 with a sawn board screwed to the parts of the element and (**b**) element 6 with fiberboard sheets glued and screwed to the parts of the element

Abb. 2 Längsverbindung der Wandelemente (**a**) Element 5, bei dem die Teile mit einem Brett verschraubt wurden und (**b**) Element 6, bei dem Faserplatten beidseitig mittels Schraubpressklebung aufgeklebt wurden

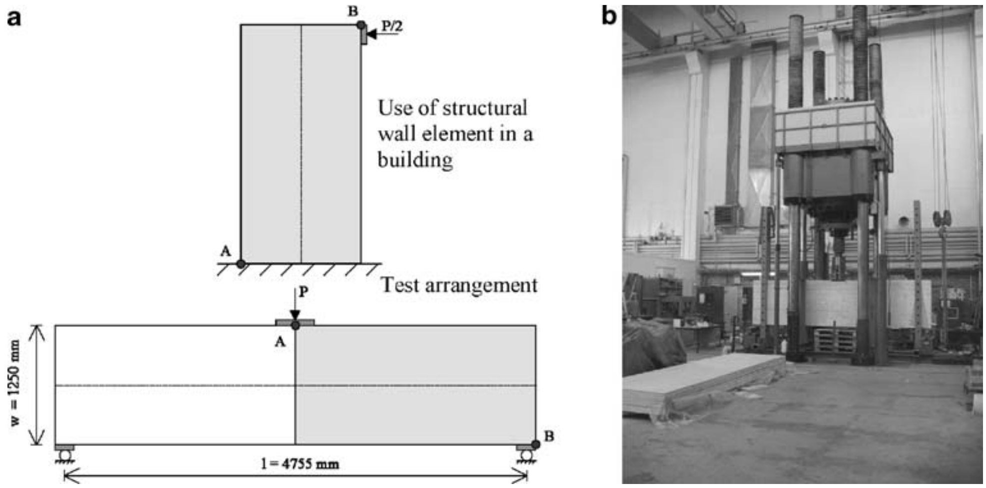

Fig. 3 (**a**) Schematic plan of the testing setup, (**b**) photograph of the testing machine. (The *dotted line* indicates a longitudinal joint such as for elements 5 and 6)
Abb. 3 (**a**) Schema des Versuchsaufbaus (die gestrichelte Linie zeigt eine Trennfuge wie bei den Elementen 5 und 6) (**b**) Foto der Prüfmaschine

Table 1 Course of events for the elements tested
Tabelle 1 Versuchsablauf der untersuchten Elemente

Element	Course of events
1	Stiffness only tested in the load interval 0–200 kN
2	Stiffness only tested in the load interval 0–200 kN
3	Stiffness test. Loading to failure
4	Stiffness test. Loading to failure
5	Made by cutting element 1 into two halves and then reconnecting the two halves by use of a sawn board screwed to the parts of the element. Loading to failure
6	Made by cutting element 2 into two halves and then reconnecting the two halves by screwing and gluing of fibreboard sheets to the parts of the element. Loading to failure

movement of the hydraulic jack proceeded at a rate of 2 mm/min.

The hydraulic testing machine had a capacity of 20 MN and the accuracy in force measurement was about ±2.3 kN for the maximum load used in this test.

In the stiffness tests the displacements were measured by use of gauges, as shown in Fig. 4. Gauges 1 and 3 were placed at half-height above the centre of the support on the left and right side, respectively, there measuring the vertical deflection above the supports, relative to the supports. Displacement gauges 2 and 4, in turn, measured the vertical deflection at half-height and mid-span on each side of the element. Gauge 5 measured the mid-deflection at half-length on the underside of the element. The displacement gauges 6 and 7 were added in testing elements 5 and 6. These two gauges were used to measure the relative slip at the ends of the longitudinal joint connecting the two parts of the elements studied.

The supports provided at the two ends held the element for vertical translation, the element being free to move horizontally at both supports. These two solid steel supports were 200 mm long and 50 mm thick, whereas the steel plate at the loading point was 400 mm long. Horizontal translation of the elements was prevented by friction at the loading point. Translation out of the plane of the elements tested was prevented by supporting surfaces of low friction. These surfaces were placed in couples on both sides of the element (at $x = 350$ mm, $x = 1450$ mm, $x = 3500$ mm and $x = 4600$ mm, x being the distance from the left support). The testing setup is shown schematically in Fig. 4, together with photos of a displacement gauge and the support arrangement.

5 Results

5.1 Stiffness

Considering the specimens tested as constituting deep beams, the deformations observed can be seen as representing contributions of three major types, those from bending, shear and local material compression, at the loading and supporting areas. Due to the orthogonal orientation of the different layers in the timber elements, the material compression could be kept relatively small. Both at the support and at the loading point, the timber was loaded parallel to the grain in two of the five layers.

The mid-deflections measured in the six specimens tested were used for determining the overall bending and shear stiffness. In Fig. 5 the mid-displacement curves obtained for

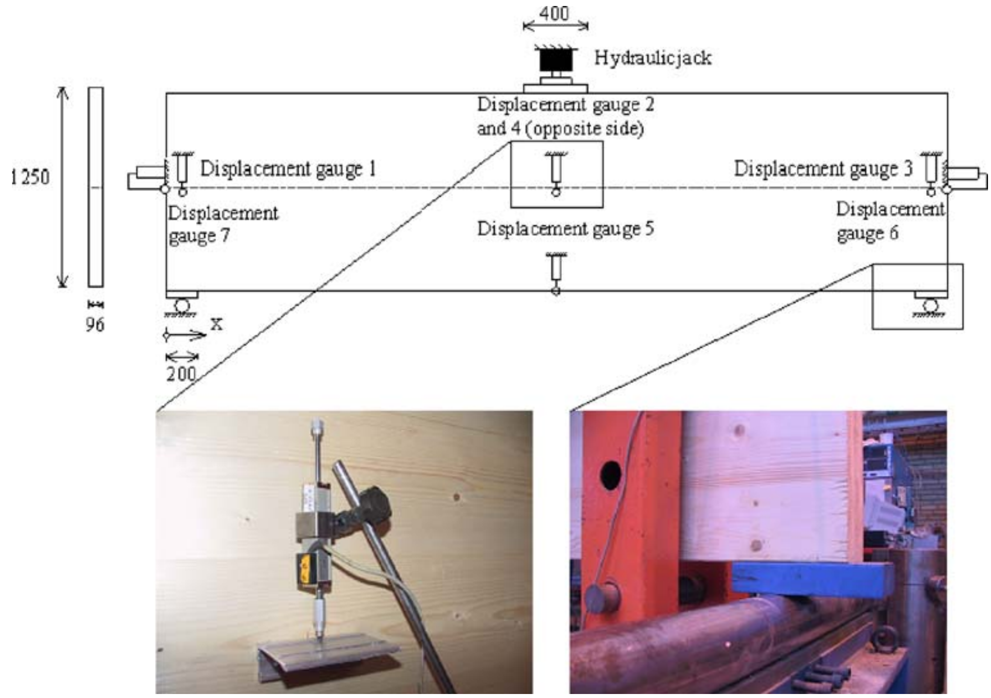

Fig. 4 Setup for measuring the displacement
Abb. 4 Vorrichtung zur Verformungsmessung

elements 1 to 6 are shown. The values presented were determined by subtracting the respective averages of the values obtained at gauges 1 and 3 from the corresponding averages obtained at gauges 2 and 4, see Fig. 4. The behaviour for each of the six elements is nearly linear. For a load of 100 kN the mid-displacement was about 3 mm for each of the elements except for element 5, where the displacement was much larger.

The displacements measured by gauges 1 and 3, see Fig. 4, provide a measure of the local deformations above the supports. Some of the results for the low load values, obtained for element 2, are shown in Fig. 6 illustrating a behaviour that was typical. Due to a non-perfect fit between the specimen and the supporting steel plates the response is nonlinear at first. From a load of about 30 kN and upwards, the behaviour then becomes almost linear. After unloading, the displacement that remained due to local deformations was less than 0.2 mm.

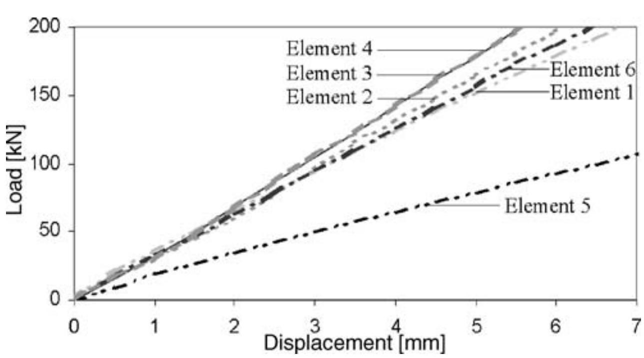

Fig. 5 Load-displacement relations for elements 1 to 6, used for determining the total stiffness in regard to the bending and shear modes
Abb. 5 Kraft-Weg-Diagramme der Elemente 1 bis 6, die zur Bestimmung der Gesamtsteifigkeit (Biegung und Schub) benutzt wurden

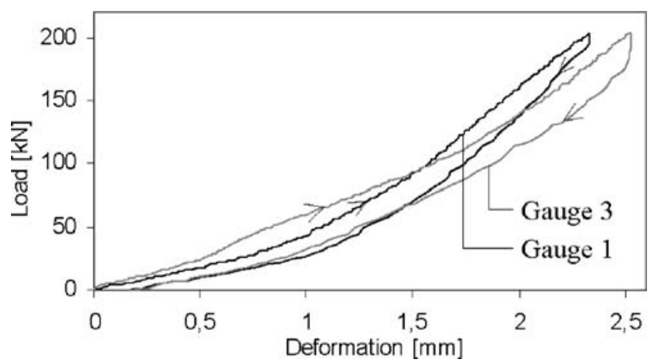

Fig. 6 Measured deformation of element 2 above the supports for a low load level
Abb. 6 Verformung von Element 2 an den Auflagern bei geringer Belastung

5.2 Loading to failure

After loading the specimens up to 200 kN and reloading, they were loaded to failure. The displacement at the loading point was gradually increased, the magnitude of the load being recorded. The load-displacement curves for elements 3 to 6 are shown in Fig. 7. Up to failure,

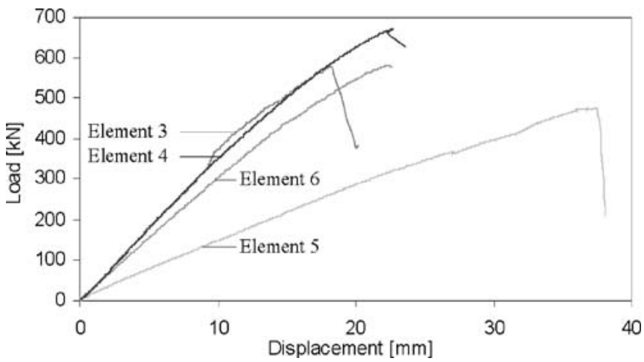

Fig. 7 Load displacement curves for elements 3 to 6 while being loaded to failure
Abb. 7 Kraft-Weg-Diagramme der Elemente 3 bis 6 bei Belastung bis zum Bruch

which occurred suddenly, each of the elements behaved almost linearly. Element 5, with its simple mechanical fasteners in the longitudinal joint, was much weaker than elements 3, 4 and 6. This indicates a considerable difference in behaviour between the two alternative ways of connections used at the joints. In contrast, the difference in behaviour between element 6, which had glued and screwed fiberboard sheets in the joint, and elements 3 and 4 without any joints, is small. It is notable how very small the difference is between the load-deformation curves for elements 3 and 4, except for the difference in failure load.

It was characteristic for all four specimens that failure occurred suddenly. Once the failure load had been reached, the entire load-bearing capacity disappeared at once, there being no ductile behaviour. Two main types of failure occurred: bending failure and local failure at the support and loading point, respectively. Elements 3 and 5 both failed in bending due to the high tensile forces the boards were subjected to, whereas elements 4 and 6 failed at the loading point and at the support, respectively. The course of event for the latter two elements was similar. At the failure load a sudden loud noise was heard when rupture of the wooden material at the support or at loading point occurred. Each of the failure modes can be seen in Fig. 8.

Table 2 provides an overview of the experimental results obtained. The stiffness defined as the ratio between the point load applied and the measured mid-deflection are based on the load interval 0–200 kN. For the reused element 1 and 2 only stiffness values can be presented and were found to be 29.7 and 33.0 MN/m, respectively. The highest failure load reached for element 4 was about 40% higher than for element 5, which likewise had an inferior joint design. Note that element 6, jointed by use of glued fibreboard, had a somewhat higher failure load than element 3 without any joint. This indicates clearly that the joint design used for element 6 worked well from a structural point of view.

In Table 2 the calculated stress values are presented corresponding to the failure loads of the specimens. The average support stress at the supports and at the loading points was calculated by assuming the stresses to be concentrated at the two layers of the cross-laminated elements where the grain direction is oriented perpendicular to the supporting plane. Also, the so-called effective tensile stress due to bending was calculated in an approximate way by considering only the three layers where the grain direction was parallel to the length of the specimens.

For an adequate serviceability state analysis of a reasonably accurate estimate of the stiffness is needed. To achieve this, the experimental results for the combined bending and shear stiffness were compared with the results of simple hand calculations based on ordinary material data and simple beam theory, including shear. The influence of each of the five layers of the cross-laminated specimens was taken into account.

The longitudinal modulus of elasticity was set to $E_l = 12\,000$ MPa and the transversal modulus of elasticity to $E_t = 400$ MPa, corresponding to an effective longitudinal modulus of elasticity of $E_{eff} = 7360$ MPa for the five layers. The shear modulus G_{eff} was assumed to be 750 MPa. On the basis of these assumptions, of the formula used, and of a loading of 200 kN, the mid-deflection becomes 7.1 mm, 55% of which is due to bending, the rest being due to shear. In the experimental test, the average displacement was 6.1 mm, indicating the value of the longitudinal E-modulus of the specimens tested to be somewhat higher than the assumed value of 12 000 MPa.

The relative slip at the ends of the joints in elements 5 and 6 was measured. The displacement gauges 6 and 7 were placed horizontally on each side of the two partitioned

Table 2 Stiffness, failure load and stress values at failure for the specimens tested
Tabelle 2 Steifigkeit, Bruchlast und Bruchspannung der untersuchten Prüfkörper

Element number	Stiffness [MN/m]	Failure load [kN]	"Effective" bending stress [MPa]	Average support stress [MPa]	Failure modes
3	35.7	577	48.0	37.6	Tensile failure in bending
4	35.8	672	55.9	43.8	Local compression failure at the support
5	14.6	475	39.5	30.9	Joint failure. Tensile failure in bending
6	30.8	580	48.3	37.8	Local compression failure at the loading point

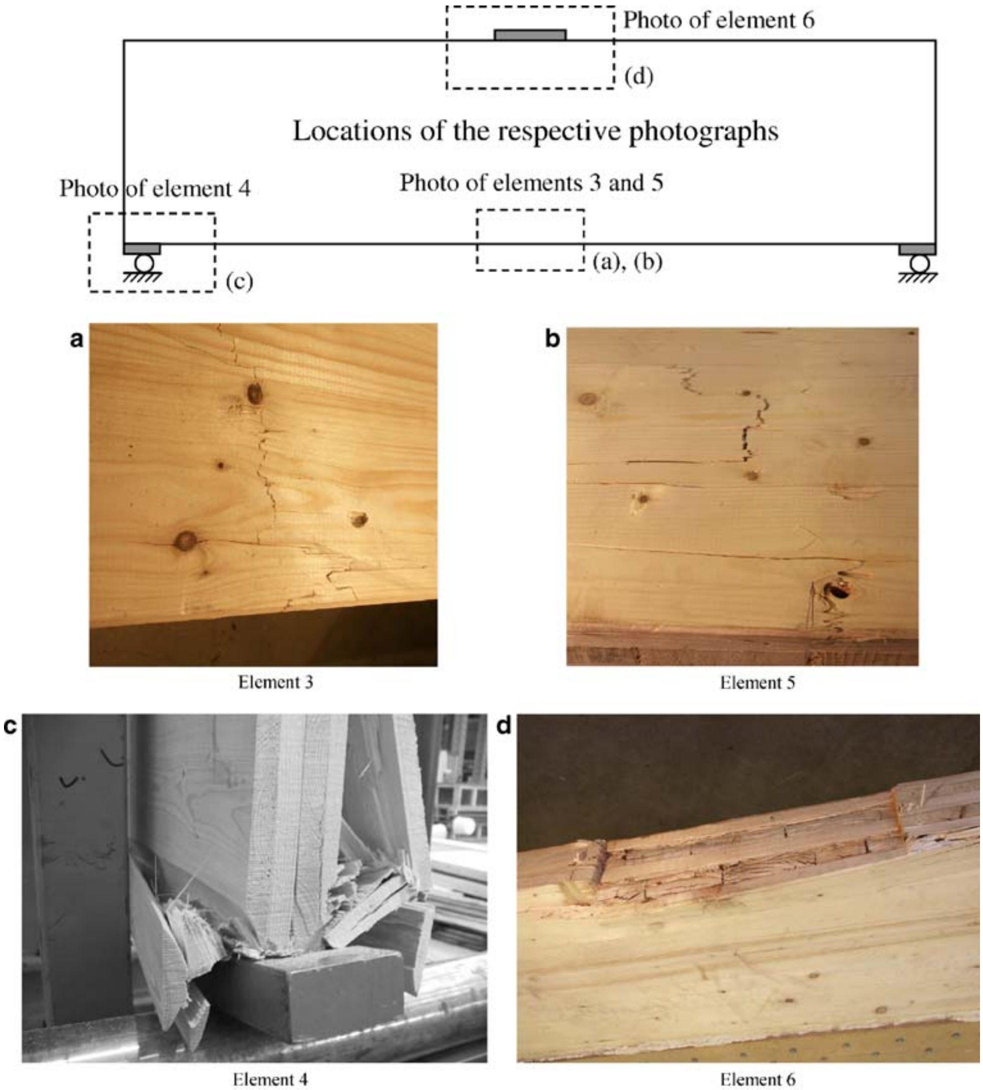

Fig. 8 Failure modes and location of each for the four elements, bending failure being involved for elements 3 and 5, and failure at the support and failure close to the load application point for element 4 and element 6, respectively
Abb. 8 Bruchbilder und Bruchstellen der vier Elemente 3 bis 6; Elemente 3 und 5: Biegebruch Element 4: Bruch am Auflager, Element 6: Bruch im Lasteinleitungsbereich

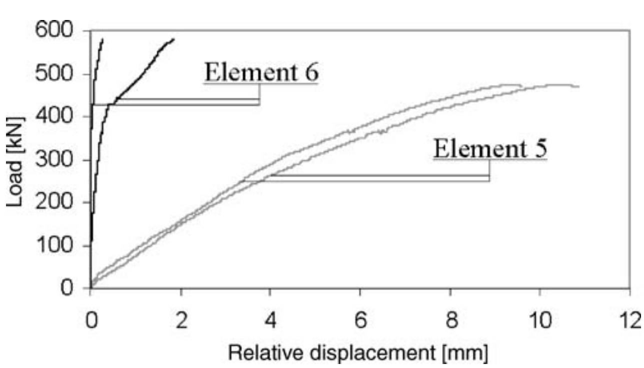

Fig. 9 The slips measured in the joints of elements 5 and 6, the measurements being made at both ends of the respective longitudinal joint
Abb. 9 Verschiebung in den Elementen 5 und 6 (an beiden Enden der jeweiligen Verbindung gemessen)

elements 5 and 6, respectively, see Fig. 4. The relative slip horizontally measured (as absolute values) between the two halves, can be seen in Fig. 9. The slip for element 5 was much greater than in the case of the glued and screwed connections used for element 6 showing further the very low degree of stiffness of element 5, which resulted in a much larger deformation of the specimen than for the other specimens tested, as can be seen in Fig. 7.

6 Conclusion

Testing a number of cross-laminated timber element specimens experimentally with respect to their stiffness and strength provided useful results. Two of the specimens were partitioned into two parts and were then reconnected, two alternative joining methods being employed. It was shown that for one of the two jointing alternatives the connection between the joined parts was just as strong and stiff as for the corresponding elements without a joint. The weaker alternative of using only mechanical connectors and a sawn board as a connecting medium is not to be recommended since the resulting strength and the stiffness were much too low.

The high level of stiffness obtained for the cross-laminated wall elements and the possibility this provided of obtaining sufficiently strong and stiff connections indicate the use of cross-laminated timber elements to have a strong stabilising potential in building construction involving timber.

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