SUSPENDED FLOOR ELEMENT CONNECTIONS FOR THE MASONITE FLEXIBLE BUILDING SYSTEM

Per-Anders Daerga[1], Ulf Arne Girhammar[2], Bo Källsner[3]

ABSTRACT: The authors present an experimental study of a suspended floor element connection (sheet steel hangers) employed in the Masonite Flexible Building (MFB) system. The hangers are mounted with screws and are pre-attached to the floor elements at manufacturing. This arrangement makes the design of the hanger critical with respect to safety and load transfer redundancy, since the screws transfer all the loads, both withdrawal and shear forces can act simultaneously. Tests have been carried out to examine the structural behaviour of the hanger. The two most critical load cases, vertical floor load and horizontal wind suction load, and three different screw joint configurations were investigated. The results indicate that the vertical distance between the screw joint and the upper edge of the rim beam should be increased and that withdrawal forces on the screws should be kept as low as possible. Some suggestions for improving the present design are given and a modified design is proposed to enhance the load-bearing capacity and to improve the overall safety and redundancy.

KEYWORDS: Suspended floor element, sheet steel hanger connections, multi-storey timber building, Masonite Flexible Building system.

1 INTRODUCTION

In timber building systems with prefabricated wall, floor and roof elements, the connections between the elements are structural key issues. In the Masonite Flexible Building (MFB) system, the floor elements are suspended to the load-bearing walls by sheet steel hangers pre-mounted on the ends of the floor elements. This procedure allows fast and easy erection of the floor and enables direct vertical wall-to-wall load transfer parallel to grain. Additional benefits are no interference with the wall envelope, a significant reduction of the vertical settling of the wall (due to no compression loading perpendicular to grain of horizontal timber members) and no heat loss at the external wall-to-floor junctions due to thermal bridges arising from intrusive floor support.

2 THE MASONITE FLEXIBLE BUILDING SYSTEM

The Masonite Flexible Building (MFB) system is a panel construction developed for multi-story residential and public buildings, with prefabricated wall, floor and roof elements which all can be customized to a high degree of completion [1, 2].

The structural carcass consist of conventional light-weight I-beams and I-studs, and a special composite laminated wood panel called Plyboard, which are mechanically joined to form a ribbed panel structure. The plyboard panel is shown in Figure 1. The wall elements are joined together with slotted-in steel-plate connections [3], while the floor elements are suspended to the walls by sheet steel hangers. The latter type of connection is the subject of this paper.

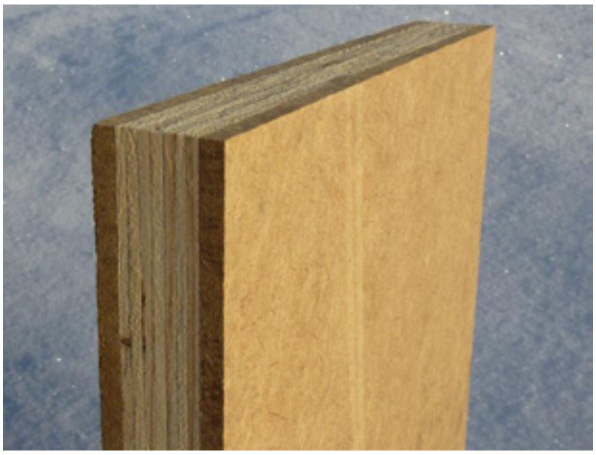

Figure 1. *Plyboard is a three-layered composite wood panel with a core of LVL and surface layers of hard fibre board. The panel is available in different thicknesses. The standard format is 1200x2400 mm.*

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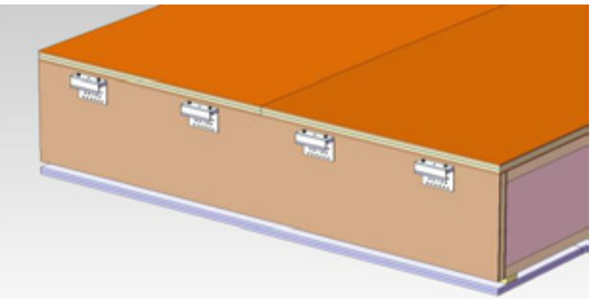
3 THE SUSPENDED FLOOR CONNECTION

The floor hangers are mounted to the end of the floor elements at manufacturing, Figure 2. The hangers are made of sheet steel and are connected by screws to the rim beam of the floor elements. At erection, the floor elements are lifted one by one and positioned in place so that the hook of the hangers grabs around the top of the perimeter beam fastened on the wall sections. The hangers are then fixed by locking screws. In order to reduce the acoustic flanking transmission an elastic damper is put between the hook and the perimeter beam. Figure 2a and b shows hangers attached to a floor element and Figure 3a depicts the hanger in detail.

The main advantage in general with the suspension concept is that the erection on site is swift and easy, and that the vertical load transfer through the wall sections down to the foundation is not interrupted by the floor, hence there is no loading perpendicular to grain as would be the case if the walls are used as support for the floor. Disadvantages are that the safety of the structure will depend solely on the hanger and that the forces to be transferred from the floor to the wall are all concentrated to the floor-to-wall connection, and as a consequence of that, load eccentricities are introduced.



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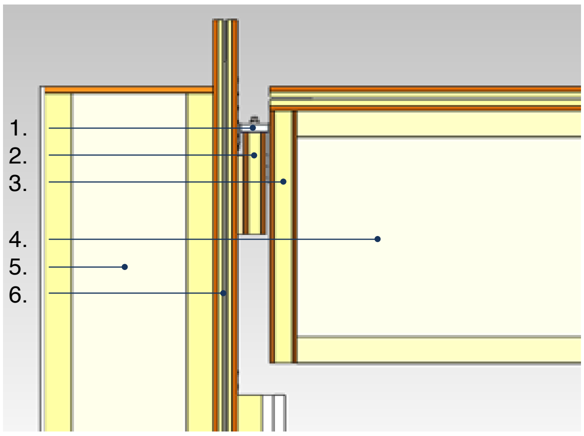


1	Floor element hanger	s 600 mm, Figure 3
2	Perimeter beam fastened to wall	12 + 39-42 mm
3	Plyboard rim beam	42 mm
4	Floor element	2400 mm
5	External wall	
6	Plyboard wall panel	42 mm

b

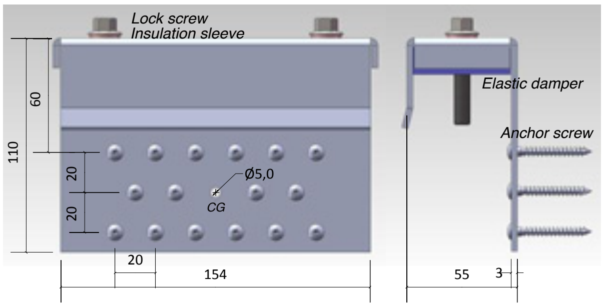
Figure 2. *The floor element hanger. (a) Hangers mounted on the end of a floor element, the spacing is normally 600 mm; (b) the floor-to-wall connection.*

In this paper, the present design of the hanger connection suggested by the company is critically examined and evaluated. Based on these finding, improvements are suggested and a new design of the suspended floor connection is proposed.

3.1 Loads acting on the floor hanger

The hanger is presently designed to withstand both the vertical floor load and the two orthogonal components of the wind load (suction and pressure) which implies a high concentration of forces subjecting the two sets of screw joints of the hanger, Figure 3b.

The load components on a hanger at the end of a floor element when the wind direction is parallel to the rim and perimeter beam are shown in Figure 3b. The red vectors are the vertical action and reaction forces from the floor load (the imposed and self-weight), the green vectors are the horizontal action and reaction forces in the length direction of the floor element due to the wind suction load and the blue vectors are the horizontal action and reaction forces parallel to the rim and perimeter beam due to the wind pressure which are transferred to the stabilizing walls via the hanger as a shear load.



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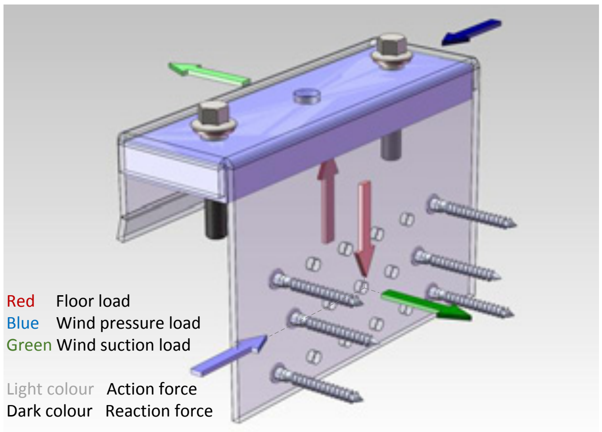

b

Figure 3. *The floor element hanger with screws and elastic damper; (a) front and side view of hanger, measures in mm; (b) resultant action and reaction forces, moments due to load eccentricities are omitted. Red = floor load, Blue = wind pressure load (transferred as a shear force to the stabilizing walls), Green = wind suction load.*

Hence, the screw connection attaching the hanger to the rim beam of the floor element is subjected to three orthogonal loads, where the wind suction gives rise to a withdrawal force while the floor and the wind pressure loads are transferred in vertical and horizontal shear, respectively. All three loads may appear simultaneously. The screw connection on the top of the hanger transfers the horizontal wind forces.

4 WITHDRAWAL AND SHEAR TESTS

To evaluate the structural behaviour and to determine the load-carrying capacity of the floor hanger in its present design, the vertical action of the floor load and the horizontal wind suction load were simulated in the tests. The floor load is the sum of the imposed load and the self-weight of the floor, and is the largest in magnitude of the prevailing loads. The forces from the wind pressure is transferred from the external wall on the windward side through the floor deck to the stabilizing walls on the sides of the deck via shear forces at the sides acting on the hanger and the perimeter beam. The load case with respect to wind pressure was not included in the test series as it is the smallest in magnitude and the most complicated to simulate in terms of boundary conditions. In addition, tests on single screws were executed to determine the withdrawal capacity of the fasteners.

4.1 Test program

The aim of the test program was to evaluate the load-bearing capacity of the hanger in "vertical" shear and "horizontal" withdrawal as a function of the number of screws (and different screw configurations). Plastic bending and possible withdrawal of the screws was the desired failure mode. However, in case of several screws in the connection failure occurred in the plyboard panel and the maximum number of screws designed for the connection could not be attained. The eccentric loading augmented the tendency for plyboard failure. Thus, the test program had to be reduced and modified.

4.2 Experimental set-up

The experiments were conducted using a test rig with a closed-loop servo-hydraulic actuator with a force capacity of 100 kN in tension and compression. The force was measured by a load-cell mounted on the actuator piston and the displacement of the connection was measured by an optical motion capture system. Figure 4 shows a rendered image of the test set-up for the shear and the tensile tests. The load was applied by inter-linked steel bars and plates with pin connectors to avoid restraints in the force chain and to obtain defined boundary conditions. The force was measured by a load-cell and the displacement of the connections by an optical motion capturing system. The same test rig was used for the withdrawal tests on single screws but with a different arrangement as shown in Figure 5.

4.3 Optical displacement measurement

An optical motion capture system using high-speed infrared video cameras and passive markers attached to test object was used for measuring displacements. The measurement system is developed and marketed by Qualisys AB [4]. The employed system featured three Oqus cameras, lightweight reflex markers, an A/D-board for synchronously data acquisition of motion data from the cameras and analogue voltage data from the load-cell, and a motion capture software (QTM) for data processing and calculation of marker position. Each camera tracks and records the 2D-movement of the individual markers, and by processing the recorded data from several cameras three-dimensional trajectories of the individual markers are obtained. The particular markers used in the tests were plastic half spheres with a diameter of 4 mm. They were attached to the surface of the test object by double sided tape.

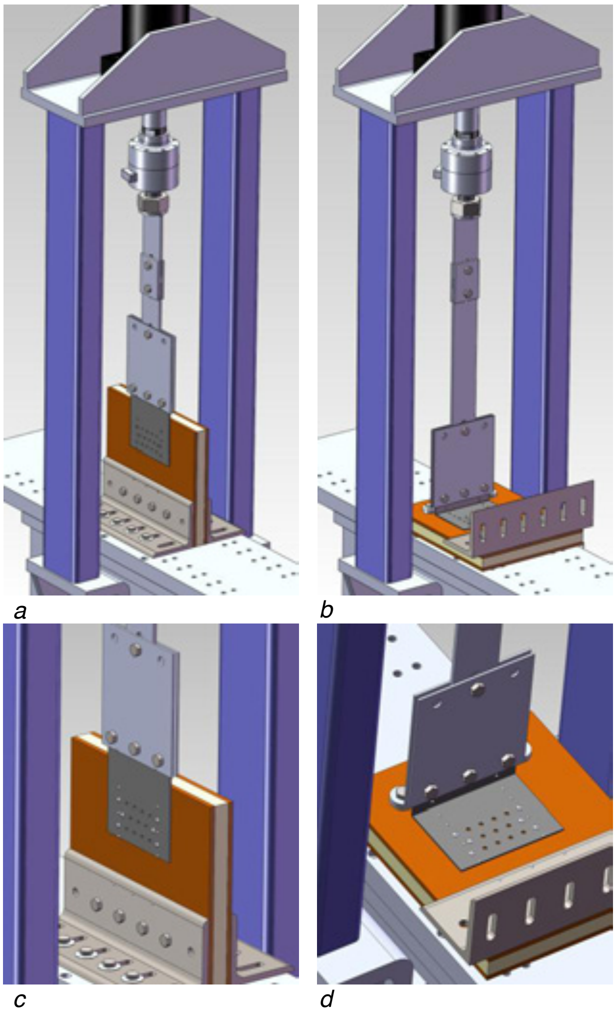

Figure 4. *Test set-up for: (a) shear test simulating vertical floor load; (b) tensile test simulating wind suction; detail of (c) shear test and (d) tensile test showing screws and optical reference markers (white) attached to the connection plate and screw heads.*

For both the shear and the tensile tests the markers were attached to the steel connection plate as well as on the head of the screws. Additional markers were attached to the foundation profiles to get an absolute reference, see Figure 4c and d, that is, the displacement of the markers on the connection are relative to the displacement of the reference markers (which are close to zero). The accuracy of the displacement measurements is better than 0.1 mm. In the withdrawal tests on single screws the displacement was calculated as the relative movement of the marker on the screw head and the three markers on the surface of the plyboard specimen, see Figure 5b.

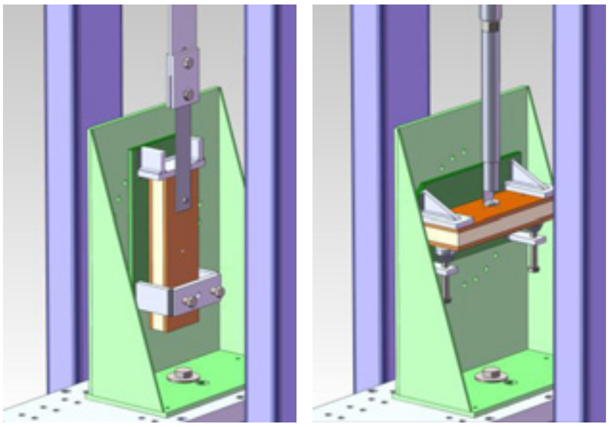

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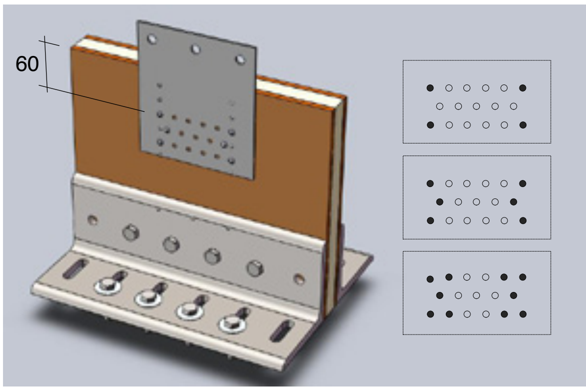
Figure 5. Test set-up for determining the capacity of a single screw connector in (a) shear and (b) withdrawal.



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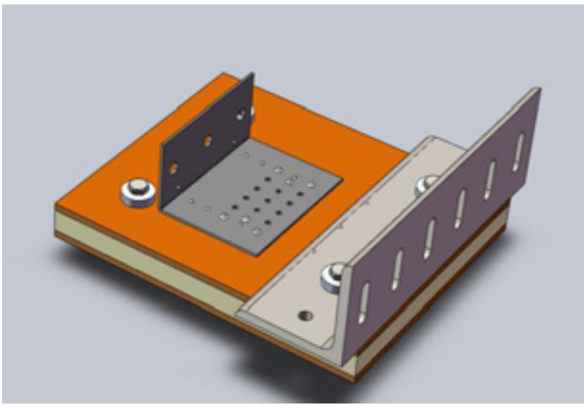

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Figure 6. The test specimens including screw configurations and foundation arrangement for simulation of: (a) the floor load and (b) the wind suction load. Edge distance is 60 mm between top of plyboard specimen and the first screw row. Plyboard specimen 360×300×42 mm (w×h×t), hanger steel plate 160×3 (w×t) of grade S355, anchor screw 5,0×40 mm.

5 TEST RESULTS AND EVALUATION

The average results of the shear and the withdrawal tests are compiled in Table 1 and Table 2, respectively, and described in the following sections. In both types of test, the specimens were loaded monotonically in displacement control mode with a rate of the actuator piston of 4 mm per minute for the shear tests and 6 mm per minute for the withdrawal tests.

5.1 Shear tests

The shear tests were carried out as shown in Figure 5a for a single screw and in Figure 4a and c for the hanger. The intention was to determine the load capacity of the hanger for several screw configurations with increasing number of screws up to a completely filled pattern. However, as the testing commenced it became evident that the eccentric mode of loading was so unfavourable for both the plyboard specimen and the anchor screws that the test program had to be adjusted. This led to three different screw configurations encompassing 4, 6 and 10 screws as shown in Figure 6a. The test results in terms of maximum load and associated displacement are compiled in Table 1, the corresponding force-displacement curves are given in Figure 7.

The eccentric mode of loading produced a skewed stress distribution across the cross-section of the plyboard specimen, with very high tensile stresses in the front fibreboard (adjacent to the steel plate), small stresses in the LVL core (due to the loading perpendicular to grain) and an almost unstressed back fibreboard, causing the load-bearing capacity of the specimen mainly to be governed by the tensile strength of the front fibreboard. The LVL core with its relatively low stiffness and strength due to the same grain orientation of all plies and loading perpendicular to grain did not contribute much to the overall load-bearing capacity.

Depending on the relation between the strength of the fasteners and the tensile strength of the front fibreboard, the ultimate failure came either as a semi-brittle bending failure of the screws or as a brittle tensile failure of the front fibreboard. The transition between these two modes of failure apparently occurred for the configuration of six screws as further described below.

Table 1. Test program and main result for shear tests.

Type of test	No of screws	No of tests	Ultimate load [kN]	Disp. at ult. load [mm]	Failure mode
Shear	1	5	6,72	7,9	A
Shear	4	8	21,0	4,0	A/B
Shear	6	5	32,6	3,4	B/C
Shear	10	2	35,7	2,9	C

A Ductile failure due to bending and withdrawal of screws.
B Brittle bending failure of screws.
C Brittle tensile failure of the front fibreboard sheet of the plyboard.

Four screws: All tests followed a similar scenario where normally one of the screws broke during loading at or just before the peak load was attained. This caused a momentarily drop of load which occasionally was followed by a regain of capacity due to internal force redistribution among the remaining screws but more often initiated an instant failure of one or two other screws, displaying as a major load drop in the post peak range of the force-displacement curve. Even after this drastic event the remaining screw(s) could rebuild the load-bearing capacity somewhat until they eventually were pulled out and the load-bearing capacity ceased. For specimen No 2, two screws broke relatively early on the ascending branch which resulted in the lowest maximum load (16.1 kN) in the set. Specimen No 1 was the only test where just one screw broke, the other where pulled out during large plastic deformations in the front fibre board, giving rise to the most "ductile" post-peak behaviour in the set. All the screws broke at the same two locations, either at the attachment of the screw head or at the transition between the threaded and unthreaded portion of the shank, see Figure 8b.

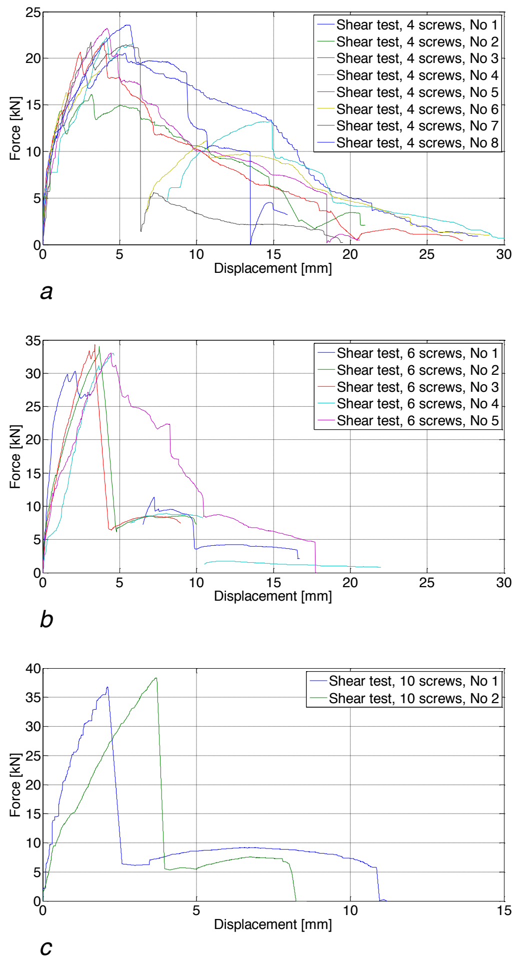

Figure 7. *Load-displacement graphs for the shear tests with (a) 4 screw, (b) 6 screws and (c) 10 screws per connection. The displacement is the average vertical displacement of the two top markers, see Figure 6a.*

Six screws: These tests displayed a mixed failure mode with features of both the four and the ten screw configuration. Test No 1 and 5 exhibited a brittle type of failure due to failure of the screws whereas tests No 2, 3 & 4 displayed tensile failure of the front fibreboard similar to the ten screw configuration. The tensile failure of the plyboard was primarily caused by the eccentric load arrangement and the fact that all the plies in the LVL-core where oriented with the grains perpendicular to the loading direction.

Ten screws: Both two tests failed due to tensile fracture of the front fibre board before the peak load was reached. All the screws remained intact, see Figure 8.

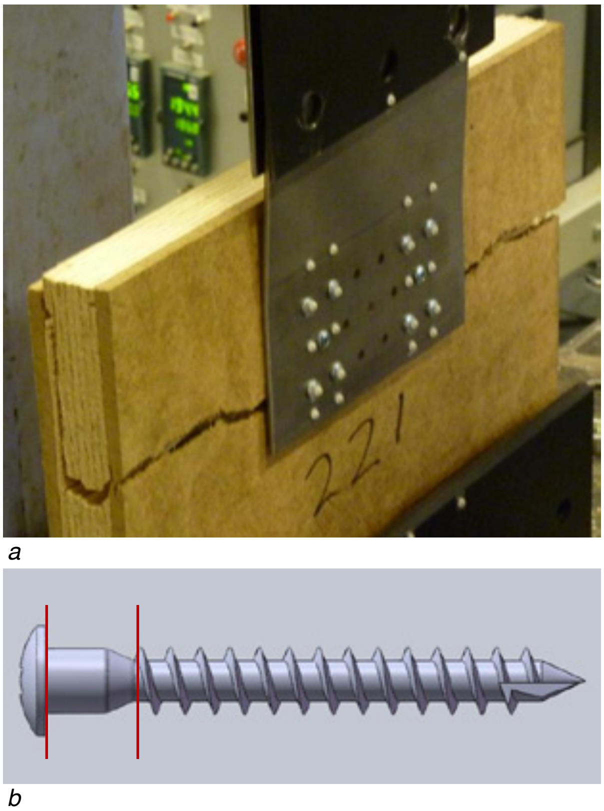

Figure 8. *(a) Tensile failure of plyboard in the eccentric shear test with the ten screw configuration. The failure was brittle due to the eccentric loading which caused the front fibreboard to essentially carry the entire load. The six screw configuration failed in the same manner; (b) Failure of the anchor screw occurred at the same two locations for both the shear and the withdrawal tests as indicated by the red lines – at the head and at the transition between the unthreaded portion and the threaded portion of the shank. Screw size 5.0×40 mm.*

5.2 Withdrawal tests

The withdrawal tests were performed according to Figure 5b for a single screw and to Figure 4b and d for the hanger. The results are compiled in Table 2, and the force-displacement curves are given in Figure 9.

Table 2. *Test program and result for the withdrawal tests (PW = Pure Withdrawal, EW = Eccentric Withdrawal).*

Type of test	No of screws	No of tests	Average ultimate load [kN]	Average displacement at ult. load		Failure mode
				Markers [mm]	Screws [mm]	
PW	1	8	3,55	-	0,59	-
EW	4	7	5,3	11,2	0.97	A
EW	6	7	6,0	14,9	1.06	A

A Ductile failure of connection due to combined bending and withdrawal of screws.

5.2.1 Tests on single screw

The single screw test gave an average load-bearing capacity of 3.55 kN and an associated displacement of 0.6 mm. The load-bearing capacity declined rather fast in the post-peak range, and was reduced to 50% of the ultimate load at a displacement of approximately 3 mm in average.

5.2.2 Tests on connection

The eccentric withdrawal tests performed on the hanger connection showed rather poor interaction between the screws, such that they were more or less pulled out row by row, starting with the row closest to the applied force. This behaviour was due to the eccentric mode of loading in combination with the flexibility of the steel sheet. Thus, the withdrawal load capacity was largely governed by the capacity of the screws in the uppermost row.

Normally at least one of the screws in the pattern failed due to combined bending and tension prior to the maximum load. The failures always occurred in the upper part of the screw and at the same two locations as for the shear tests, see Figure 8b. Figure 10 shows test No 4 of the six screw configuration where it can be seen how the steel sheet has folded along the screw rows and that three screw heads have popped off.

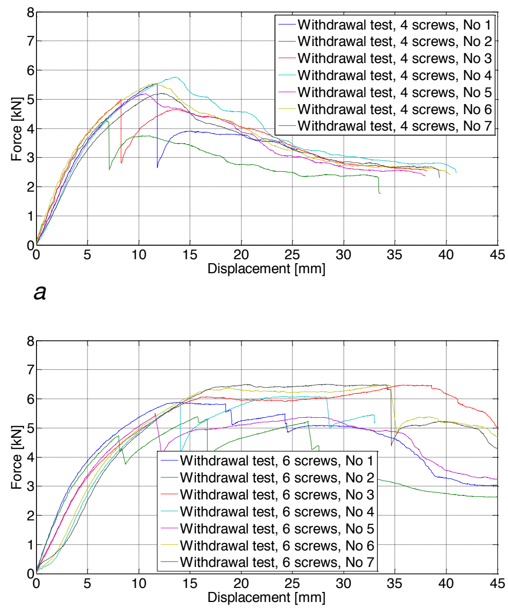

Figure 9. *Load-displacement graphs for the withdrawal tests with (a) 4 screw and (b) 6 screws per connection. The displacement is the average vertical displacement of the two top markers, see Figure 6b.*

The eccentric mode of loading reduced the load-bearing capacity of the connection considerably and the low stiffness of the sheet steel decreased it further more. The poor interaction between the screws is illustrated in Figure 11 for test No 3 of the six screw configuration. The finished test is shown in figure a, the complete average force-displacement curve in figure b, the ascending branch up to maximum load in figure c where the displacement is from the individual top markers. Figure d illustrates the displacement profiles along the two lines of markers. It is readily noticed how the screws in the row nearest to the applied load takes most of the load while the screws in the third row remained unloaded up to the maximum load.

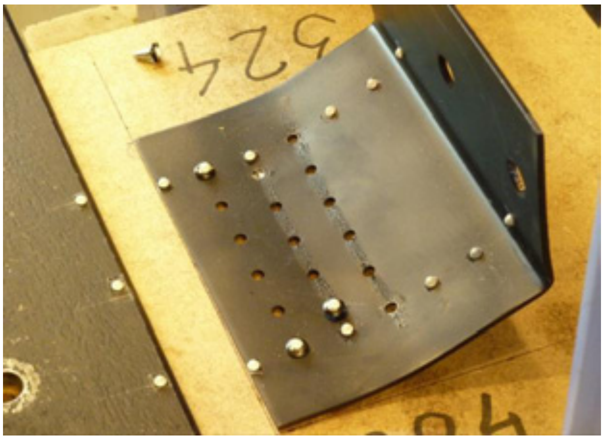

Figure 10. *Photo depicting test No 4 after finishing withdrawal test. It can be observed that the steel sheet is folded along the row of screws and that three screw heads have popped off.*

6 TEST EVALUATION AND REDESIGN GUIDELINES

The eccentric mode of loading in both the shear and the withdrawal tests revealed limitations in the prevailing design of the hanger, the plyboard rim beam and in the performance of the fasteners. The eccentric shear loading prevented the load-bearing capacity of the plyboard to develop to its full potential for reasons explained in Section 5.1, and are likely to induce a brittle tensile failure of the plyboard for high design loads requiring a denser screw configuration than the six screws configuration causing the failure in the tests, Figure 8a.

Similarly, the eccentric withdrawal loading hindered the full load-bearing capacity of the fasteners to develop due to the screws were pulled-out row by row, starting with the row nearest the applied force. The rows further away remained latent until the load capacity of the preceding row was exhausted.

Even the screws were negatively affected by the eccentric mode of loading in both types of tests. The loading introduced a high bending moment in the top portion of the screw which frequently caused failure in the partially unthreaded shank. The failure occurred at two locations of equal incidence; at the attachment of the head to the shank (causing the head to pop off) or at the transition between the unthreaded and the threaded shank as illustrated in Figure 8b. The latter coincided with a change from a conical to a cylindrical cross-section.

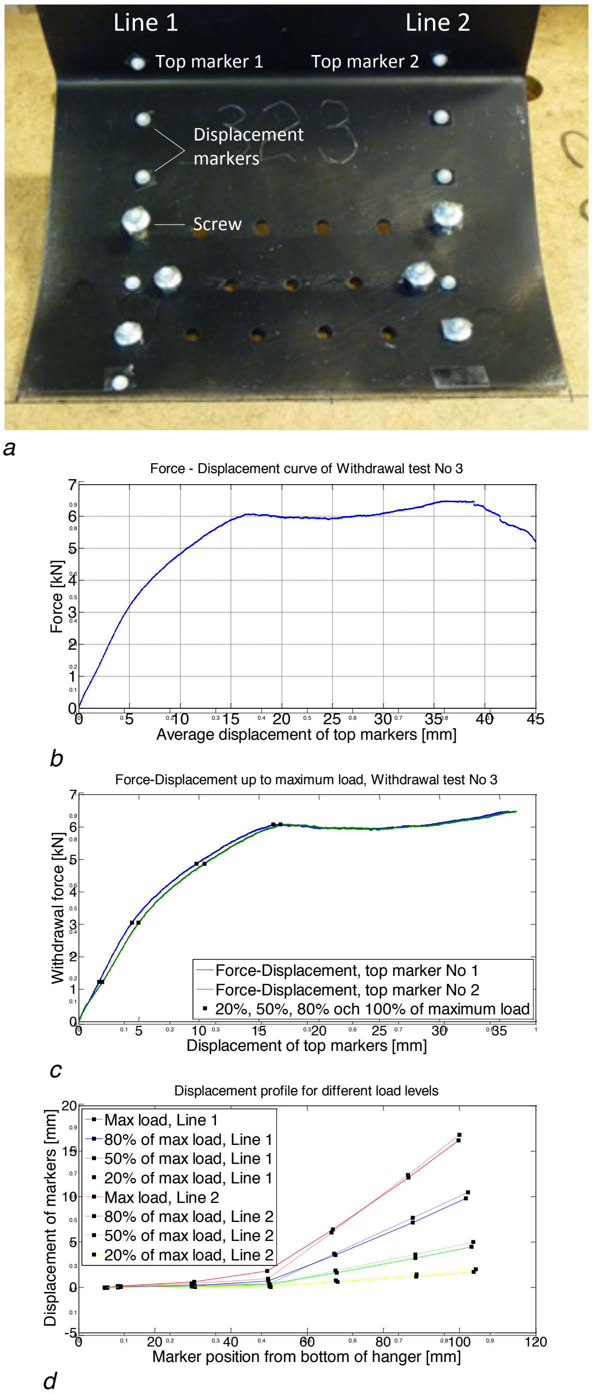

Figure 11. *Interaction of screws in the withdrawal test No 3 with a six screw configuration; (a) Specimen after finished test showing the screws and the displacement markers arranged along two lines. The displacement of the individual markers were recorded and ordered in a displacement profile along each line; (b) The complete force-displacement curve where the displacement is the average of the two top markers; (c) The ascending force-displacement curves up to the maximum load where the displacement is from the individual top markers; (d) The displacement profile of each line at load levels 20%, 50%, 80% and 100% of the maximum load. It can be observed that screws in the first row are pulled out much more than the other screws and that the screws in the third rows remain unloaded up to the maximum load.*

A way to improve the present design of the hanger would be to change the grain direction of the LVL core. The rim beam will essentially not be bent and, therefore, the grain of the LVL could be arranged vertically to enhance the tensile capacity of the rim beam. Also, bolts could be used with tightening nuts on the backside of the plyboard to incorporate the capacity of the fibre board on the opposite side. An additional strengthening effect would be obtained if the steel plate of the I-beam hanger could be included in the suspended floor connection. The evaluation of these suggested improvements to the present design is not discussed further in this paper.

The experimental findings call for a change of design of the hanger in order to enhance the usage of the plyboard and screws and obtaining a more ductile mode of failure.

6.1 Design guidelines

The structural objective for designing the hanger is to alter the mode of loading such that the components of the connection can be utilized to their full capacities. Based on the experimental outcome, the following guidelines are stated for redesigning the hanger:

1. *Separating the loads:* A significant simplification would be to separate the three orthogonal loads such that the hanger would accommodate the imposed load and the self-weight of the floor while the wind suction load and the wind pressure load are directly transferred to the stabilizing wall through the top floor panel. This would eliminate the load eccentricities introduced by the wind loads, which in the present design go through the hanger connection. Thus, separating the loads would clarify the structural behaviour of the hanger and simplify the calculations in the ultimate limit state.
2. *Avoiding withdrawal of fasteners:* The anchor screws showed low displacement capacity (0.59 mm) in the single screw withdrawal test, and poor interaction when the connection was tested in eccentric withdrawal. Thus, withdrawal loading should be avoided or at least reduced as much as possible.
3. *Attaining ductile behaviour:* The plyboard rim beam and the screws both failed in a brittle manner without reaching their inherent capacities due to the eccentric mode of loading. The redesign should consider a change of loading mode that favours a more ductile failure.
4. *Retaining swift and easy erection of the floor element:* This feature is already achieved in the present design and should be kept the same.

6.2 New design proposal

A radical change of design would be to alter the path of load transfer so that the forces are transferred directly from the bottom flange of the floor I-beam to the perimeter beam on the load-bearing wall without going through the rim beam. This can be accomplished by integrating the floor hanger and the beam hanger into one hanger unit. The rim beam becomes almost unloaded but is still needed for stabilizing the floor element frame and for providing support for the integrated hanger.

A design proposal is shown in Figure 12. The hanger accounts only for the vertical floor load. The wind loads are transferred directly from the floor panel to the load-bearing wall by steel angle brackets.

The design is statically determinate. The two screws at the top and the bottom channel profile accommodates the horizontal forces which are introduced to counteract the moment due to the eccentricity of the vertical forces.

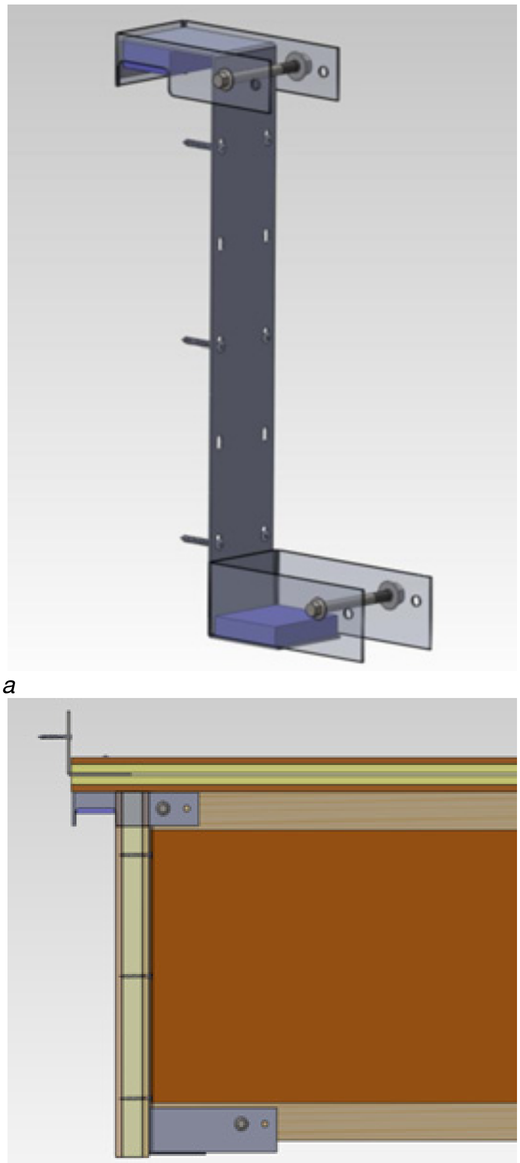

Figure 12. *Proposed integrated beam and floor hanger. (a) Perspective view. The top and bottom channel profiles are shown transparent, blue pads are elastic dampers; (b) Side view of a floor element with the hanger inserted. The hanger carries only the vertical load, the horizontal wind load is accommodated by angle brackets attached to the floor panel. The rim beam is shown transparent, the floor finish and the ceiling are not shown.*

The acoustic flanking transmission is considered by elastic dampers on the bottom and top part of the hanger. Embedding the main body of the hanger inside the frame of the floor element provides good fire protection. Also the protruding top part and the bottom part are assessed to receive adequate fire protection from the floor panel and the ceiling respectively.

7 DISCUSSION AND CONCLUSION

Suspended floor structures have several features which are favourable for multi-storey timber buildings. By attaching the floor elements to a perimeter beam on the load-bearing walls, the floor and the wall is structurally separated, implying that:

- the wall envelope remains intact,
- there is no loading perpendicular to grain at the wall-floor junction, hence the vertical settling of the wall may be kept to a minimum,
- thermal bridges are avoided,
- the erection of the floor is easy and swift.

The main challenge is to accomplish the floor-to-wall connection such that both structural and functional demands are satisfied.

The experimental results of the prevailing floor element hanger suggest that the design should be changed in order to avoid brittle failure of the plyboard rim beam, reducing the withdrawal forces on the screws and minimizing the risk for screw failure. The basic cause for these problems is the eccentric mode of loading exerted by the vertical (floor load) and the horizontal (wind suction) load.

A new design of the hanger is proposed which combine the functionality of the floor element hanger and the beam hanger into one hanger unit, hence overcoming much of the problems originating from the eccentric mode of loading. The design is based on the guidelines formulated in Section 6.1. Additional features like fire protection and acoustic flanking transmission are also considered. Numerical analysis of the design proposal is planned in order to optimize the design.

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