Racking behaviour of structural insulated panel (SIP) walls

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Summary
In the UK and Europe traditional studded timber frame walls sheathed with wood based sheet material and/or plasterboard are now often replaced with Structural Insulated Panel (SIP) wall systems. SIPs are used as principal loadbearing wall components in domestic and light industrial construction, currently up to three storeys in height. The racking performance of SIP walls is very different from the structural timber frames they replace. The principal differences in wall composition between the studded timber frame and sandwich panel walls lead to inaccuracies and in cases overestimation of sandwich wall racking performance using standard procedures. This paper details the differences between SIPs and timber frame racking performance and discusses the effect of these differences on the use of standard design methods for SIP walls.

1. Introduction
SIPs are prefabricated lightweight building units, used as principal loadbearing components in domestic and light industrial construction, in Europe currently up to three storeys in height. In Europe the panel systems are mainly used as loadbearing internal and external walls. The SIP discussed in this paper consists of two high density face layers which are bonded both sides of a low density, cellular core substrate (figure 1). A strong, structural bond between the three layers is essential to the loadbearing ability of the composite panel so that high loads can be transmitted by the relatively light units without internal studding.

In Europe the face layers of the panel are usually cement- or gypsum based building boards and also Oriented Strand Board (OSB). The materials used as core substrate are diverse and range from synthetic, rigid foam cores, such as extruded and expanded polystyrene (XPS and EPS) or polyurethane (PUR) and its derivative polyisocyanurate (PIR), to inorganic mineral fibre. Self-adhesive, synthetic foam cores, such as PUR and PIR, are suited to a continuous production process of the pre-fabricated panel systems and are commonly used in Europe.

![Figure 1: Structural Insulated Panel (SIP)](image-url)
With respect to racking performance, sandwich walls are a derivative of timber frame construction. Therefore the racking design of structural sandwich walls currently relies on the timber frame design procedures as outlined in BS EN 594 [1], BS 5268 Sectio n 6.1 [2] and EN1995-1-1 [3]. This is due to the similarities between both wall construction types and because loadbearing sandwich walls construction method have too small a current use to justify a dedicated design method.

Whilst both wall systems have commonalities in their reaction to in-plane loading, the distinctively different panel composition of structural sandwich walls does impact on the applicability of the timber frame design guidance. Using the available guidance is likely to lead to inefficiencies in use and in some cases performance will be over estimated. The provision of a dedicated design method for sandwich panels is not a simple procedure due to the variability of SIP systems. The study assessed three panel systems and covering a range of design influencing features. The panel systems were chosen so that the influence of the various panel components, namely boards, core (only foam or foam with internal solid units), connection method (bottom/ top rail and vertical joint) and fixings could be examined. The study also assessed the influence of wall parameters such as height, vertical loading, length and openings on the racking performance of structural sandwich walls. The findings of the investigation into the effect of length and openings will not be reported here.

The critical design factor in most structural sandwich wall systems is the provision of adequate fire resistance and this will govern the choice of the panel components. Whilst the racking design is secondary in importance, some of the panel components chosen to enhance the fire resistance of the walls can also be beneficial to the racking performance. The knowledge about the fact that some factors are of little importance to fire but rather critical to racking (such as the base fixings) can help the complementary design of walls, which can be adjusted to suit both loading/ exposure scenarios.

2. Test programme

The effect of board and core material, their glued bond, the inclusion of internal stud units as well as the bottom and top rail configuration and the effect of fixing method potentially have influence on the wall racking performance of sandwich wall construction. Whilst timber frame walls are built to standard dimensions with regards to stud/ rail dimensions, spacing of studs, the construction of vertical board joints, the use of fixing patterns and edge nailing distances, these factors may be non existent in sandwich wall construction or can vary considerably depending on the specific wall system.

The three systems chosen for this investigation are representative of systems available to house builders in the UK and vary in board and core materials, but also with respect to top and bottom rail connections, vertical jointing and fixing methods. Whilst systems 1 and 3 are considered to be in frequent use in the European market, system 2 with glued connections is more commonly used in the US.
3. Results
Below the findings are summarised. Detailed information cannot be included in the current format but can be found in [4].

3.1 Influence of board
As in timber frame walls the veneers of a sandwich wall are the main load resisting components in a shear wall and their fixings to the horizontal and vertical connectors are influential to the overall wall performance. In sandwich walls too, the board materials affect the performance with respect to their failure behaviour at the front and rear end of the wall. The board materials assessed within the programme could broadly be subdivided into two groups in accordance with the performance of boards in timber frame walls:

(i) brittle behaviour boards such as the cement-based board used in system 1,
(ii) ductile behaviour boards such as the OSB used in system 2 and 3.

The characteristic board failures for both types of board were identical to those witnessed in timber frame tests. However, the sandwich wall results also showed that seemingly advantageous board characteristics can be overridden by the bottom rail design, discussed later. In sandwich walls clad with brittle boards the influence of tolerances in the joints can become a major issue especially in systems where an internal, recessed horizontal rail or vertical connection mechanism is used. If the construction is too tight the likelihood of the board breaking along its length/height is probable. This destroys the continuity in the wall and can have major impact on the walls’ racking performance.

3.2 Influence of core/ additional internal units
It could be found that the core material has almost no influence on the racking resistance, provided that it is stiff enough to prevent the faces from moving independently; a

### Table 1: Wall systems investigated

<table>
<thead>
<tr>
<th>System</th>
<th>Materials</th>
<th>Rails</th>
<th>Vertical Joint</th>
<th>Fixing method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Boards/</td>
<td>Core</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 (2.7m)</td>
<td>CBPP (8mm)</td>
<td>PUR (70mm)+internal units</td>
<td>Cold-formed steel (t=1.13mm)</td>
<td>Intermittent hook</td>
</tr>
<tr>
<td>2 (2.4m)</td>
<td>OSB (11mm)</td>
<td>EPS (100mm)</td>
<td>Timber narrow (90x40mm)</td>
<td>OSB tongues</td>
</tr>
<tr>
<td>3 (2.4m)</td>
<td>OSB (11mm)</td>
<td>EPS (100mm)</td>
<td>Timber wide (12.5x40mm)</td>
<td>OSB tongues</td>
</tr>
</tbody>
</table>

Notes:
1: Bottom and top rails are identical, used inverted
2: Cement-bonded particle board
3: For this panel system the influence of fixing method was investigated, nails and glue were compared
condition usually satisfied in structural sandwich panels. Additional internal studding does not impact the racking performance. However, in panels assembled with narrow bottom rails, where the veneer are free to rotate and move, an compression strong end stud at the rear end of the wall enhances performance. A strong unit at the end of the wall unit restricts the down throw of the panel and thereby reduces the uplift, providing additional strength throughout the wall. Further improvement can be expected when internal units and bottom rail are connected directly so that the rotational movement is resisted not only by the board and its in plane shear strength but also by the internal units acting as a stiffening uplift reinforcement.

3.3 Influence of bottom/ top rail
The bottom and top rail construction is a major influencing factor to the racking resistance of a SIP walls. The construction and type of the horizontal connection influences on the racking resistance of the sandwich wall in two respects
(i) rigidity of the bottom rail
(ii) the shape of rail (bottom and top connection)

![Figure 2: Influence of rigidity of bottom rail (specifically ahead of first holding down bolt)](image)

The rigidity of the bottom rail affects the uplift of the panel at the windward front end of the wall. The stiffer the bottom rail the smaller the uplift of the panel ahead of the first rail fixing reducing the overall deflection of the wall. The softer, more bendable the bottom rail the larger the uplift measured in the front of the panel. The veneer capping thin cold-formed steel u-channel employed as bottom rail construction in system 1 is particularly weak and bends. The wooden bottom rail in the system 2/3 panels performs stiffest, due to the increased rail thickness and the short span ahead of the first holding down bolt (figure 2).

The shape and design of the bottom and top rail has major impact on the racking performance and more importantly on the vertical load reaction of structural sandwich walls. Three rail designs were tested in the programme. The bottom/top rails in system 1 and 3 allowed the direct bearing of the veneers, whereas system 2 rail offered no restraint to sheathing other than the fixings along the rail. The set-up of system 2 is similar to traditional timber frame.
The free rotation of the veneers especially at the rear end of the wall, induces early and abrupt failure, which is aggravated under vertical loading. Figure 3 compares the racking performance of the wall systems 2 (narrow rail) and 3 (wide rail) under vertical top loading. This effect will be discussed further in section 3.6 “Influence of vertical load”.

3.4 Influence of vertical joint
The vertical joint between two panels is of less importance to panel performance than the bottom rail influence, especially at zero vertical load. However the stiffer the joint between panels the better the racking resistance of the wall assembly. The differential movement between two single units should be as small as possible as this prevents the panels from rotating independently as separate units. This can be appreciated in the comparison of system 1 and 2 (figure 4).

Although system 1 uses the wide rail connection, the flexibility of the rail together with the weaker intermittent jointing at the vertical intersection contributes to the inferior stiffness and strength performance. Despite the fact that the hook system performs reasonably well in tension and compression, its performance when subjected to in-plane shear deformations of the wall is negligible. Vertical joint made of glued tongues, are advantageous as they connect the single panels rigidly, reducing differential movement between the single panels to a minimum. This rigid connection connects the two panels to one single large panel, which increases the racking performance of the wall.
3.5 Influence of fixing method
The fixings connecting panel veneers and bottom rail have major influence on the panels’ strength and stiffness performance. This was apparent in the test series of systems 2, in figure 5, which is commonly built by gluing the panels at the intersections, along the bottom and top rail and the vertical joint. The glued connections perform well providing constant fixity to the ductile board material. As a consequence the panels exhibit high stiffness and strength values in the tests, however, due to the failure mechanisms with glues the overall failure of the units is abrupt and extensive damage in the glue line along the bottom rail is apparent. Glued connections are generally the most powerful fixing method, as shown before for the glued bottom rail and vertical joint connections. Nail and screw fixings are more common in the UK building industry.

Figure 5: Influence of fixing method: Glue vs nails

A panel’s failure behaviour is more ductile when it is connected using mechanical fasteners and the effect of vertical load is more closely related to timber frame construction. When the glued connections in system 2 were replaced by nails the strength and stiffness of the wall unit was reduced by 25%, (figure 5). With nailed connections the failure was more ductile and 90% of the maximum load was maintained over 30mm deflection. The narrow soleplate used in the nailed panel tests will have exacerbated the reduction in performance.

In panel systems using brittle boards the influence of edge distance is marked. The closer the fixing to the edge of the board the less its resistance to in-plane shear and break out and strength performance is likely to be reduced, however stiffness should remain unaffected.

3.6 Influence of vertical load
When analysing the findings of the racking test programme it could be seen that the design of the bottom rail detail had major impact on the performance of the wall, especially when the shear wall was vertically loaded (see section 3.3). Here the governing factor was the width of the rail allowing the free rotation of the veneers as opposed to the enclosing rail, where the veneers were restricted from moving independently of the rail. This was seen to enhance the basic racking resistance of the sandwich walls when compared to standard timber frame, where the veneers rotate without external restriction. Whilst the narrow rail configuration resembles the set-up encountered in standard timber frame panels, the detrimental effect of vertical load on the sandwich wall performance is very much in contrast to the enhancement in performance encountered in vertically loaded timber frame walls. In this design scenario the vertical loading applied augments the compression loading along the bottom rail of the panel unit, especially at the trailing
end of the wall unit. In the wide, veneer enclosing rail design, the performance of the shear wall enhances with vertical load as the vertical load reduces the tensile forces at the front of the wall without unduly adding to the compression stress in the down-throw zone of the wall at the rear. In such sandwich walls the performance does improve with vertical load, but not to the same extent as encountered in timber frame (wall performance under vertical load is 1.77 times the performance at zero vertical load). This could be shown for both, stiffness and strength performance. The timber frame design approach is generally governed by the strength behaviour of the shear wall, which seems to be similar applicable for structural sandwich walls.

For both SIP generic bottom/ top rail configuration types the improvement by vertical load cannot be accurately predicted using current guidance. Figure 6 shows that the vertical load performance of structural sandwich walls needs to be adapted depending on the bottom rail connection used in the wall. Systems 1 and 3 profit from the vertical load and higher strength performances are encountered under 25kN top loading. In System 2 (narrow bottom rail) the performance with vertical loading is reversed.

Therefore systems with wide bottom railed walls can be designed using an enhancement factor. This is similar approach to timber frame, although not to the same extent. Sandwich wall systems with narrow rail connections are not safe to be designed based on timber frame theory and need a new design approach.

**3.7 Influence height**

The conversion presented in the BS 5268 [2] for wall heights between 2.1m and 2.7m is thought to be equally valid for structural sandwich walls and safe in use. However both types of walls, timber frame as well as sandwich walls would profit from a more sophisticated approach as suggested by Enjily et al., 1996 [5], by adopting a shape factor summing the effect of height and length.

**4. Summary**

The racking behaviour of structural sandwich walls is affected by generally the same factors as timber frame walls. In both types of building systems the sheathing board type and thickness and its fixing to the underlying construction are the main influencing factors and determine the racking performance and in plane deflection of the wall. However, due to the different framing structure sandwich walls have a wider range of reactions under vertical loading. Whilst timber frame panels always benefit from vertical loading structural sandwich walls can be weakened by vertical loading. The effect of
vertical loading on structural sandwich walls is dependent from the bottom rail configuration of the wall, which throughout the work has been established as the overriding design issue. Two types of sandwich wall have been distinguished

(i) sandwich walls horizontally linked by a bottom/ top rail, which allows the free rotation of the veneers,

(ii) sandwich walls with a rail configuration, which restricts the free rotation of the veneers.

Whilst vertical loading reduces the performance of the type (i) structural sandwich walls, the single panels interlinked by the wider bottom rail (type (ii)) profit from vertical load similar to timber frame. Although sandwich walls with type (ii) bottom rails have similar performance improvement under vertical load the magnitude of improvement is not the same as in timber frame. This is also related to the rail design and is suggested to be included in the racking design through a “rotational restraint effect”, increasing the performance of the walls at zero vertical load and reducing the enhancing effect of vertical loading.

The internal studding placed in the walls for enhanced fire resistance could be used to mutually benefit the racking performance if the stud units could be rigidly connected to the bottom rail. In these walls the racking resistance at 0kN vertical load could be further enhanced since the board in the uplift zone of the wall in the front would be reinforced, achieving higher loads at lower deflections.

The effect of height on sandwich wall performance have been confirmed similar to timber frame and the modification factors suggested in the current British Code [2] and EN1995-1-1 [3] are deemed to be safe for the use with structural sandwich wall assemblies. However, this will need to be confirmed through an enhanced test programme, confirming the trends laid out in this work.

Calibration studies to establish the applicability of EN1995-1-1 procedures for SIP structures are currently being undertaken.

References


