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# Lateral stiffness of cold-formed steel shear wall panels braced with glass panes: A numerical study

Bert Van Lancker [1], Delphine Sonck[2], Wouter De Corte[3], Jan Belis[4]

**Abstract**

Cold-formed steel shear wall panels can often be found in residential, commercial and office buildings. Such load-bearing walls, consisting of a cold-formed steel frame with structural sheeting screwed onto it, act as primary lateral load resisting component that has to maintain the stability and integrity of the structure. Although these panels have some unique advantageous properties, they are characterised by small openings due to closely spaced studs (i.e. the vertical frame members). To increase the building's transparency, the load-bearing capacities of glass can be utilised by bracing the frames with glass panes instead of traditional sheeting. For this purpose, the traditional screwed connection is transformed into a circumferentially linear adhesive connection between frame and glazing. This modification results in an altered behaviour of the newly developed hybrid cold-formed steel-glass panel compared to a traditional panel. In this research, the aim is to determine the different influence factors on this behaviour by performing a literature survey. By means of numerical modelling, the horizontal stiffness of these newly developed shear wall panels was assessed in the serviceability limit state and the relative displacements between the glass panes and the cold-formed steel frame were determined. This paper reports about the significance of the influence of the width-to-height ratio of the panel, the thickness of the adhesive layer, the thickness of the frame members, the glass thickness and the type of section used for the frame. To find the optimum configuration for given design conditions, all investigated influence factors had to be taken into account, even though their significance varied. The width-to-height ratio, the adhesive thickness and the glass thickness up to values of 8 mm had the most significant influence on the overall behaviour of the hybrid cold-formed steel-glass shear wall panels.

*Keywords:* Cold-formed steel, shear wall panel, adhesive, CFS-glass connection, numerical modelling

[1] PhD canditate, Ghent University
[2] Doctoral Assistant, Ghent University
[3] Professor, Ghent University
[4] Professor, Ghent University

## 1. Introduction

Although in building construction cold-formed steel (CFS) members were originally used as secondary load-bearing elements (e.g. purlins, sheeting, etc.), their effective use in primary load-bearing structures of residential, office and commercial buildings has been acknowledged in recent years. This is due to the more efficient production of high strength steel and more economic steel coils, which are subsequently formed into light gauge sections by roll forming, folding or press braking. The high strength and stiffness, lightness, ease of production, recyclability and non-combustibility of cold-formed steel increased the use of CFS to improve structural and serviceability building performance.

Cold-formed steel shear wall panels (CFSSWP) are an example of the use of CFS in primary load-resisting elements (Fig. 1). Such panels consist normally of tracks (top and bottom), studs, bracings and connections, which can be assembled either in the factory or on site. The studs are fastened to the tracks at their ends, hence the tracks distribute the loads among the studs and act as their lateral support. The studs themselves act as gravitational load-resisting members. The lateral load-bearing capacity of the frame has to be sufficient to resist the lateral load or racking load caused by wind, earthquakes or even transportation in case of prefabrication. Bracing the frame with structural sheeting, such as Oriented Strand Board (OSB), plywood, etc., which is screwed onto it, significantly increases its capability to carry vertical and lateral loads.

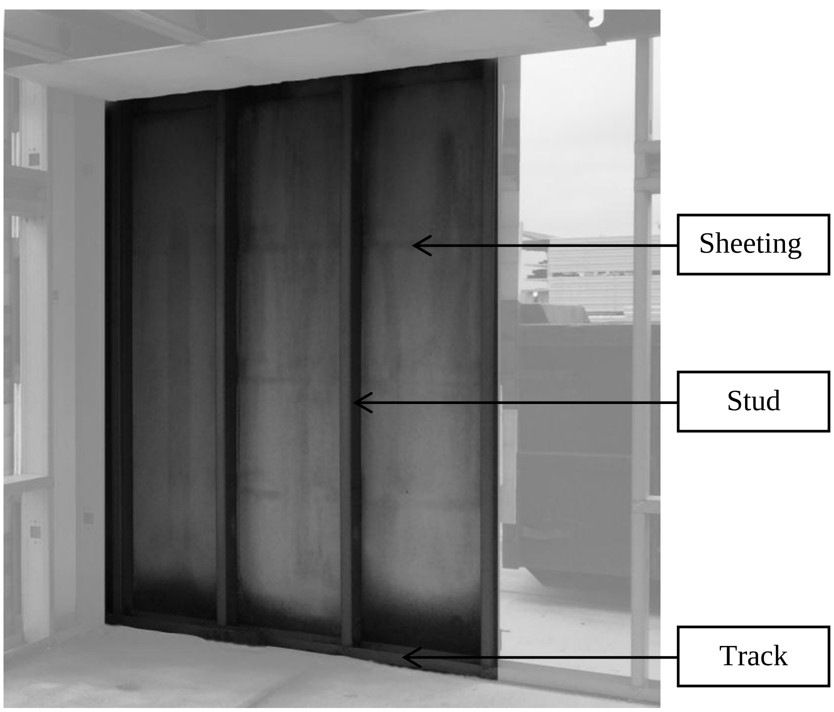


Figure 1: Cold-formed steel shear wall panel and its basic components

Notwithstanding the unique properties of cold-formed steel structures, the transparency is limited due to closely spaced vertically aligned studs, which create only small openings. Architects nowadays strive for maximum transparency, achieved by large glazed areas. In this mind-set, the possibility of cold-formed steel frames sheeted with circumferentially adhesively bonded glass panels is investigated. Thus, the traditional CFSSWP braced with screwed structural sheeting is transformed to a CFSSWP braced with an adhesively bonded glass panel.

In such a hybrid CFS-glass shear wall panel, the load-bearing capacities of the glass are utilised. In research by Wellershoff (2006) and Huveners (2009) on circumferentially adhesively bonded glass panes in steel frames, the load-resisting capacity of the glass was activated, which demonstrated the good prospect of structural glass elements. Research on load-bearing timber–glass shear walls (Ber et al. 2014, Hackspiel and Fadai 2014, Serrano et al. 2014) confirmed the potential use of glass for these applications as well.

During the transformation of a traditional CFSSWP with screwed structural sheeting to a CFSSWP with adhesively bonded glass panes, the type of connection changes from a discrete screwed connection to a continuous linear adhesive connection. Consequently, a proper selection of a suitable adhesive is important. Based on former research on glass-metal adhesive connections (Belis et al. 2011, Overend et al. 2011, Van Lancker et al. 2014), the structural silicone Sikasil SG-500 was selected as a suitable adhesive for the application of a frame-supported glass structure.

This research aims to investigate the lateral stiffness of a cold-formed steel shear wall panel braced with glass panes on both sides which are adhesively attached to the frame along the circumference. First, the influence factors on this lateral behaviour of the hybrid CFS-glass panel are determined. Therefore, by means of a literature survey, the influence parameters on the behaviour of traditional CFSSWPs are identified and classified. Based on this overview, the parameters that could possibly influence the behaviour of the newly developed concept are identified. By means of numerical modelling, the importance of the influence of several of these parameters of the horizontal stiffness and the composite behaviour of the panel in the serviceability limit state is studied. The width-to-height ratio of the panel, the thickness of the adhesive layer, the thickness of the frame members, the glass thickness and the type of section used for the frame are considered within this study.

## 2. Influence factors on the behaviour of CFSSWPs

Since the research on the stabilising properties of sheeting started in the 1940s (Green et al. 1947), intensive studies have been performed to examine the influence of six basic factors, differentiated in several parameters, on cold-formed steel shear wall panel behaviour (Fig. 2). These studies were executed using an experimental, numerical or analytical methodology. Firstly, the experimental approach consists mostly of full scale tests of which the results can be compared to design values given by building codes (UBC 1997, IBC 2015). Although this approach is very expensive, it is still the most applied one. The limited applicability of the experimental results for a CFSSWP with other geometrical and material characteristics than the ones used in the tests can be evaded by developing a calibrated numerical model. Lastly, the available literature regarding analytical approaches to determine the lateral strength and stiffness of CFSSWPs is rather limited. Most methods are based on the analyses of sheeted wood shear walls, as the global response is qualitatively very similar (Easley et al. 1982, McCutcheon 1985).

In the 1970s and 1980s, Tarpy (1984) conducted intensive research on the influence of aspect ratios, sheeting thickness, fastener spacing, and construction and anchorage details on the shear strength and resistance of steel stud wall systems. Miller and Peköz (1993, 1994) investigated the effect of sheeting on the vertical load-bearing capacity of cold-formed steel studs. Valuable results on the shear resistance of CFSSWPs sheeted with gypsum were obtained by Serrete and

Ogunfunmi (1996). However, knowing that research on the topic of CFSSWPs in general was already going on for over 60 years, research on the racking behaviour of CFSSWPs was rather scarce. It is just since the beginning of the new millennium that a lot of new research has been conducted at several universities around the world. In Cambridge, Tian et al. (2004) focussed on the lateral behaviour of CFS frames subjected to monotonic lateral in-plane loads. Both an experimental and analytical approach were used. Fulöp and Dubina (2004) conducted experimental research on full-scale sheeted CFSSWPs and validated a numerical model. Fiorino et al. (2006) proposed an analytical method for predicting the nonlinear shear versus top wall displacement relationship of sheeted CFSSWPs. Xu and Martinez (2006) proposed an analytical method to determine the ultimate lateral strength of the shear wall panel and its corresponding displacement that could be used in engineering practice. At McGill Univeristy, researchers tried to develop guidelines for seismic application of CFSSWPs sheeted with wood panels (Branston et al. 2006). Another research project aimed to establish a database of information on steel sheeted CFSSWPs and to derive a corresponding design method (Balh et al. 2014). Cold-formed steel members braced with structural sheeting were thoroughly investigated at Johns Hopkins University (Schafer et al. 2009, Vieira and Schafer 2012, 2013, Peterman and Schafer 2014), which led to a proposal for a new design method (Schafer 2013).

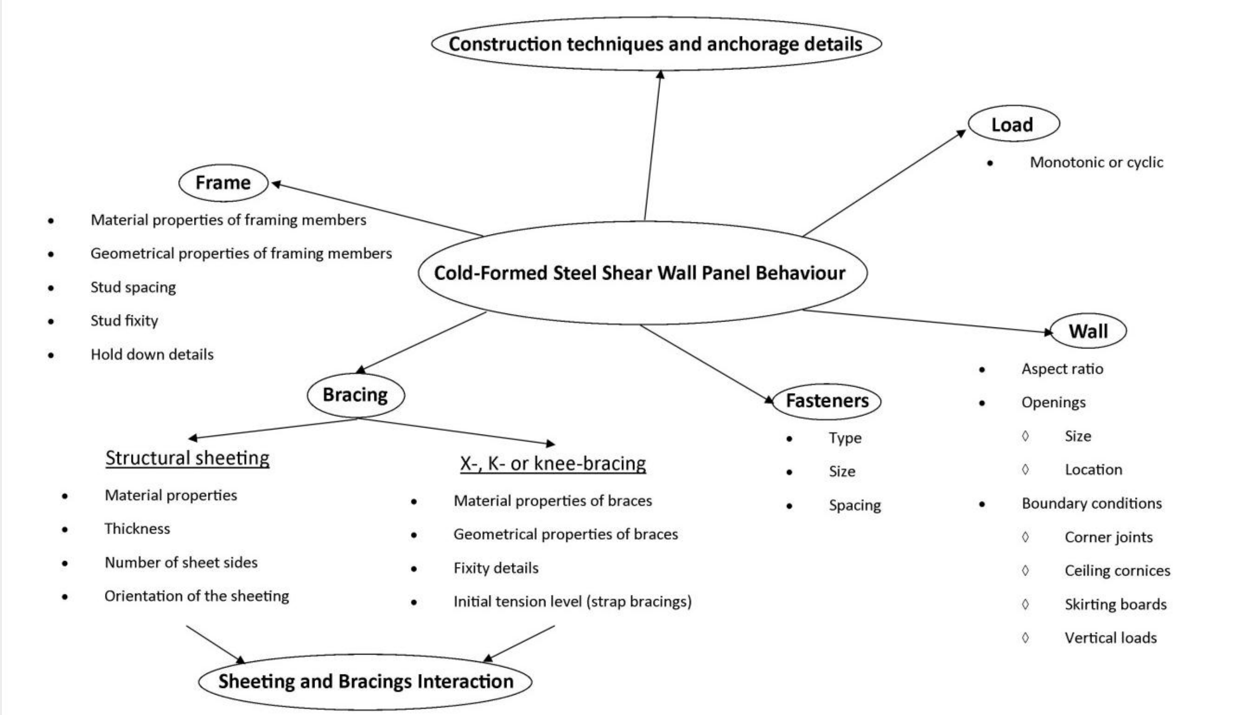


Figure 2: Influence factors on the behaviour of CFSSWPs based on Gad et al. (1999)

In Fig. 2, the influence factors on the behaviour of traditional cold-formed steel shear wall panels with screwed structural sheeting are described. Based on this figure, the influence factors on the behaviour of a cold-formed steel shear wall panel braced with circumferentially adhesively bonded glass panels can be determined (Fig. 3). Again, six basic factors can be distinguished, based on identification of the basic factors of traditional CFSSWPs. The categories that remain the same are: Construction techniques and anchorage details, loads, wall and frame, as fundamentally there is no difference between the traditional concept and the new one. However, the type of sheeting and connection between frame and sheeting do change. Hence, the basic factors bracing and fasteners are transformed to glass and adhesive, and for each category, parameters are differentiated as has been done for the traditional CFSSWP.

Using Fig. 3 as starting point, a finite element model is developed to determine the significance of several parameters for the lateral behaviour of a hybrid CFS-glass panel in the serviceability limit state. These parameters are: width-to-height ratio, adhesive thickness, glass thickness, section thickness and type of section used for the frame.

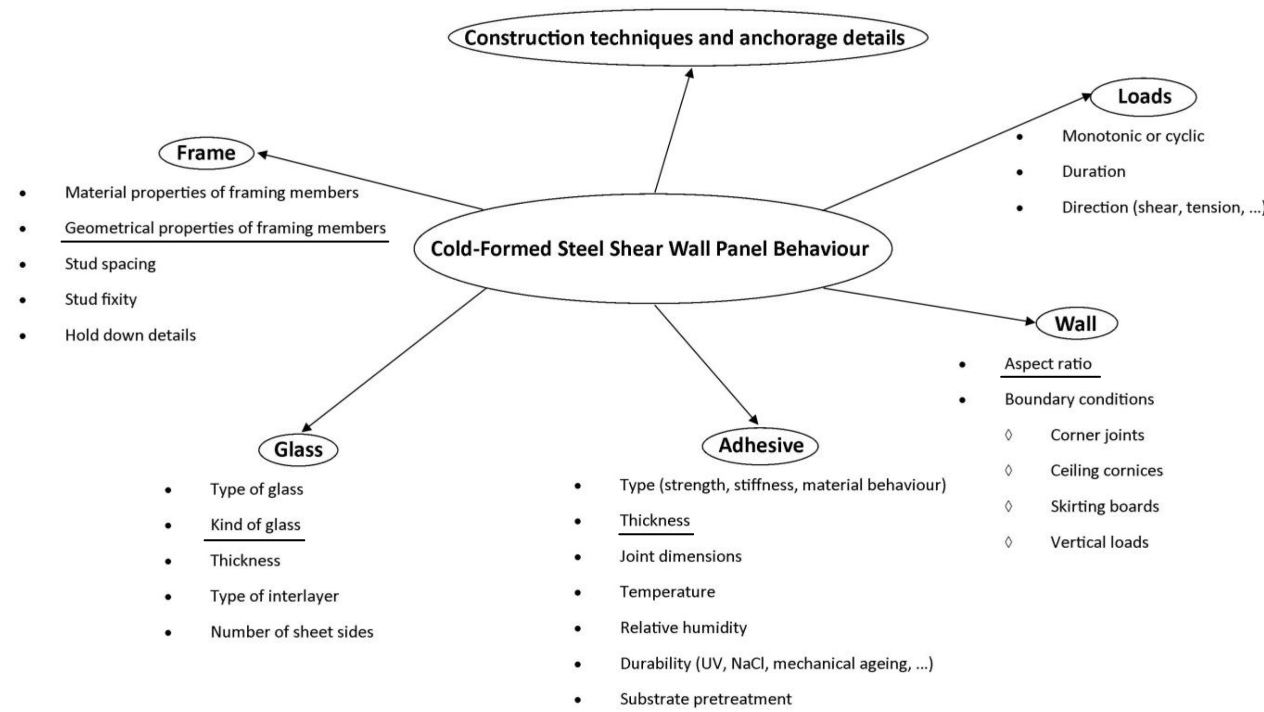


Figure 3: Influence factors on the behaviour of hybrid CFS-glass shear wall panels

## 3. Finite element model

ABAQUS®, a finite element analysis software, was used to develop a three-dimensional numerical model of a cold-formed steel frame braced on each side with a circumferentially adhesively bonded glass panel (Fig. 4). The reference configuration consisted of a 2.4 m by 2.4 m frame, composed of two commercially available C-shaped studs (C100x2) connected to the corresponding top and bottom U-shaped track (U100x2) by means of five screws at each stud-to-track connection. On both sides of the frame, annealed glass panes with a nominal thickness of 12 mm were adhesively connected to the flanges of the studs and tracks. Sikasil SG-500 with a nominal thickness equal to 6 mm was used. As the U-shaped tracks slide over the C-shaped studs, the thickness of the adhesive on the studs was larger than the adhesive thickness on the tracks, which has to satisfy the minimum required thickness.

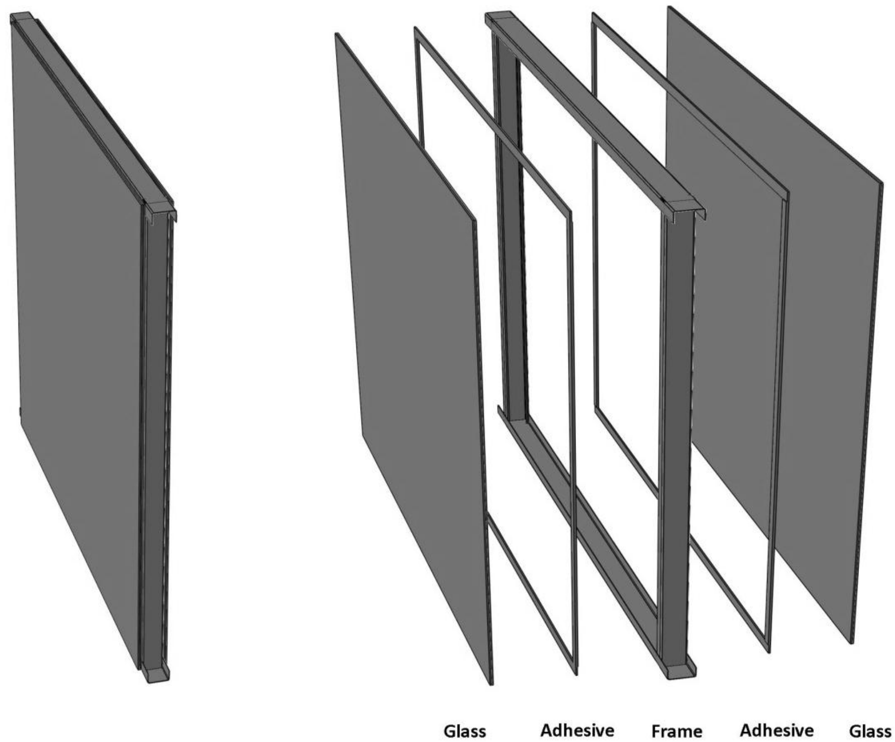


Figure 4: Normal (left) and exploded (right) sketch of a hybrid CFS-glass shear wall panel

The CFS sections were modelled using a four-node, quadrilateral, stress/displacement shell element with reduced integration and a large-strain formulation (S4R). In practice, the screws will be made of steel with a higher yield and tensile strength than the studs and tracks. Consequently, for simplicity, the screws were idealised by coupling all degrees of freedom except the rotation about the axis of the fastener at the stud-to-track connections. Hence, slip in the screwed connection is neglected. On the studs and tracks, the adhesive Sikasil SG-500 was modelled as a three-dimensional solid with eight-node hybrid linear brick elements (C3D8H). The glass itself was modelled using the same four-node three-dimensional quadrilateral shell elements (S4R) as used for the frame.

The cold-formed steel sections were assigned a perfectly elastic-plastic material model, with a Young's modulus of 210 GPa, a Poisson's ratio of 0.3 and a yield strength of 390 MPa, based on the commercially available steel quality S390+Z275 for CFS sections (Van Lancker et al. 2014). The glass was assumed to behave perfectly linear elastically with a modulus of elasticity equal to 70 GPa and a Poisson's ratio equal to 0.23. For the Sikasil SG-500, hyperelastic material properties were modelled with the Neo-Hooke material law. The coefficients of this material law were determined based on uniaxial and planar test data provided by the manufacturer.

The frame was considered to stand on a fixed surface, hence the bottom track was not able to move in a vertical direction. At the position of the left stud, the bottom track was assumed to be screwed to the fixed surface and for simplicity a hinged connection was modelled. On the right side, a roller support was assumed, corresponding with the assumption of a slotted hole in the web of the bottom track parallel to the surface of the panel. For the top track, the out-of-plane horizontal displacements were restrained at the positions of the studs (Fig. 5).

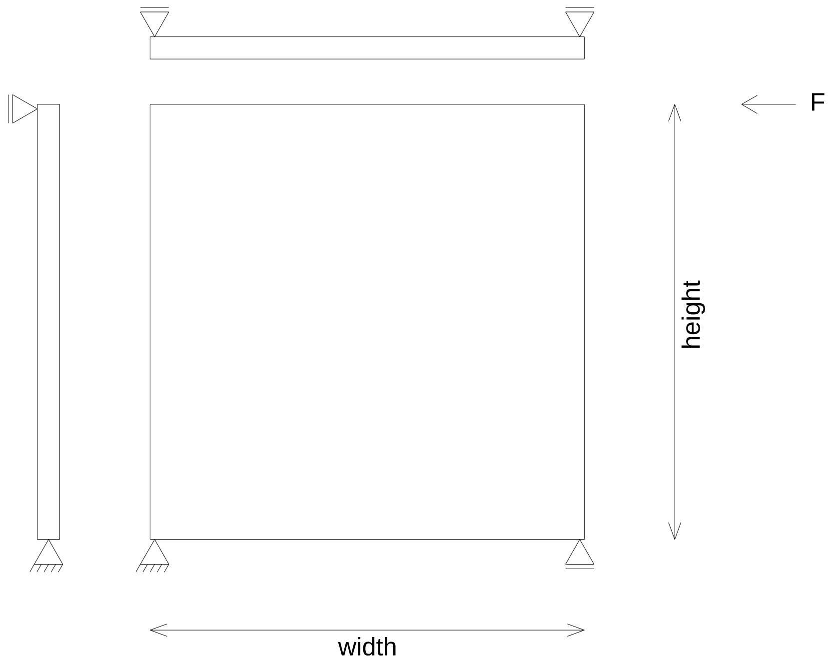


Figure 5: Boundary conditions

The hybrid CFS-glass shear wall panel was loaded horizontally in-plane at the end of the top track. Therefore, a rigid body of the nodes at the end section of the top track was defined and a constant displacement was applied on the reference node. Based on limit values for the deformation of structures in the serviceability limit state (BIN 2003), a displacement of 6 mm was used.

A geometric and material nonlinear analysis (GMNA) was performed for several configurations, varying the width-to-height ratio, adhesive thickness, glass thickness, section thickness and type of section used for the frame (Table 1). A measure for the horizontal stiffness $k_h$ of the panel was defined as the ratio of the applied horizontal displacement to the horizontal reaction force of the anchorage after linearization of the force-displacement diagram. Further, the relative displacements between the glass panes and the studs of the frame were determined in terms of the average difference in rotations of the frame ($\varphi_{frame}$) and the glass panel ($\varphi_{glass}$) at the position of the studs (Fig. 6). The determined values were always compared with respect to the reference configuration ($k_{h,ref}$ and $\Delta\varphi_{ef}$).

Table 1: Investigated parameters

| Parameter | Unit | Range |
|---|---|---|
| Width-to-height ratio | [-] | [1:4, 1:2, 1:1, 2:1, 4:1] |
| Adhesive thickness | [mm] | [2, 4, 6, 8, 10] |
| Glass thickness | [mm] | [2, 4, 6, 8, 10, 12, 15, 19] |
| Stud section1 | [-] | [C80x1.5, C80x2]<br>[C100x1, C100x1.25, C100x1.5, C100x1.75, C100x2]<br>[C150x1.5, C150x2] |

[1]Cxx-yy represents an C-shaped section with a height of xx mm and a thickness of yy mm. The section width for C80-sections equals 40 mm, whilst for both C100- and C150-sections this value equals 50 mm.

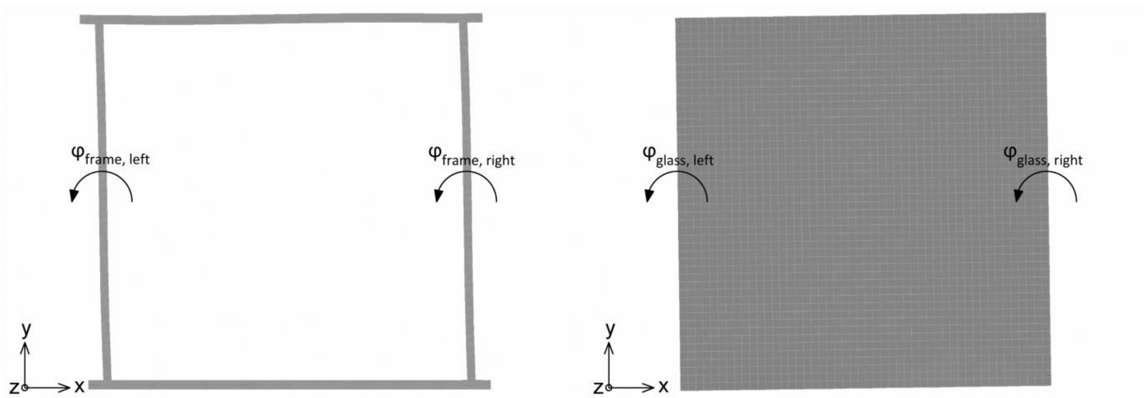


Figure 6: Rotations of the frame (left) and the glass panes (right)

# 4. Results

## *4.1. Influence of width-to-height ratio*

When the width-to-height ratio increased, the lateral stiffness of the hybrid CFS-glass SWP increased as well (Fig. 7). A ratio greater than one resulted in a stiffer CFSSWP (159.7 % and 202.8 % of the reference stiffness for a ratio of 2 and 4 respectively), whilst a ratio smaller than the unity resulted in more flexibility of the panel (30.7 % and 8.2 % of the reference stiffness for a ratio of 1/2 and 1/4 respectively). Also the relative displacements between the framing members and the glass panes increased with increasing width-to-height ratio. For a ratio of 1/4 and 1/2, this measure reached values of 14.2 % and 48.9 % of the reference value. The relative displacements for a ratio of 2 was 3.3 times greater than in case of a ratio equal to one and for a ratio of 4, even a value of 8.4 times the relative displacements of the reference was reached.

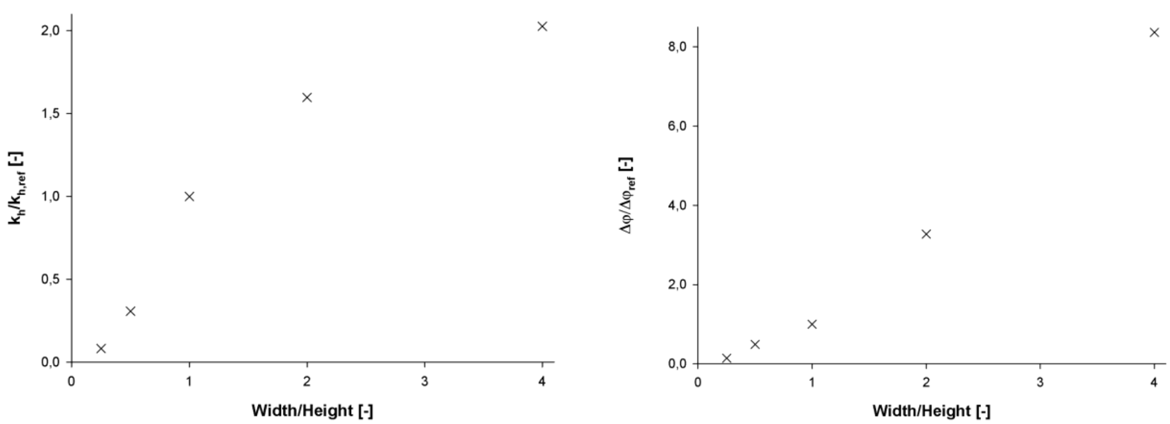


Figure 7: Influence of width-to-height ratio on lateral stiffness (left) and relative displacements between glass pane and frame (right)

## *4.2. Influence of adhesive thickness*

Increasing the adhesive thickness from 2 mm to 10 mm resulted in a decrease of the horizontal stiffness of the panel (Fig. 8) and an increase in relative displacements between the framing members and the glass panes. Hence, a thicker adhesive layer caused larger relative displacements because of its increased flexibility. Therefore, the glass is less activated and composite action is reduced, which results in a lower horizontal stiffness of the hybrid CFS glass panel. For example, in case of a 2 mm thick adhesive layer, an increase of 78 % in lateral stiffness and a reduction of 20.1 % in relative displacements compared to a 6 mm thick adhesive layer can be observed. Although, both effects are beneficial (higher stiffness and more composite action), the influence of this parameter is more profound for the horizontal stiffness. However, a minimum adhesive thickness of 6 mm is imposed for structural sealant glazing systems (EOTA 2005). Hence the values of 2 and 4 mm are rather theoretical values, although further optimisation of the adhesive joint could be worthwhile.

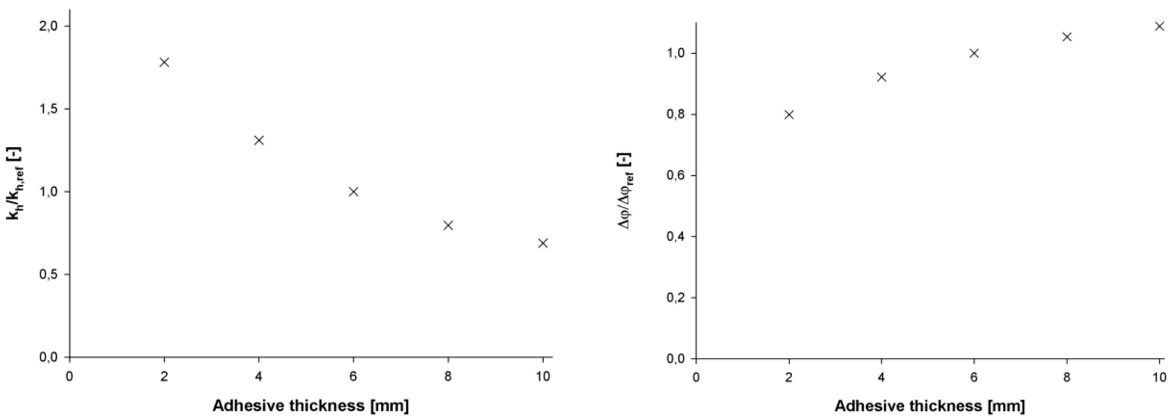


Figure 8: Influence of adhesive thickness on lateral stiffness (left) and relative displacements between glass pane and frame (right)

*4.3. Influence of section thickness*

When the thickness of the cold-formed steel frame members was halved (1 mm instead of 2 mm), the lateral stiffness of the hybrid CFS glass SWP decreased by 23.5 % (Fig. 9). In case of 1.25 mm thick sections, this decrease in stiffness was only 7.9 % compared to the 2 mm thick sections. The relative displacements between glass panes and the frame members decreased for decreasing section thicknesses, as less material in the frame is available to directly absorb and transfer the loads. Hence, the glass will be more activated to assist and thus composite action is more present.

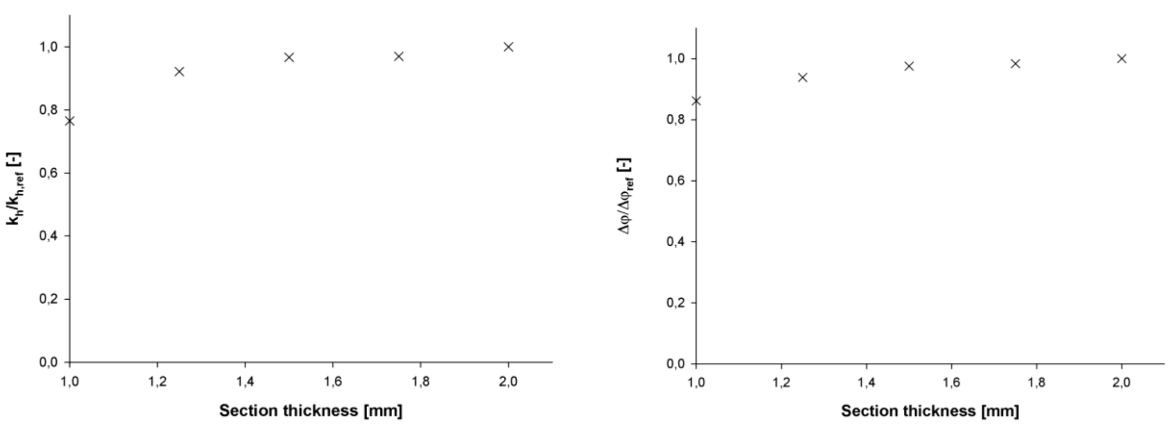


Figure 9: Influence of section thickness on lateral stiffness (left) and relative displacements between glass pane and frame (right)

*4.4. Influence of glass thickness*

If the glass thickness varied from 2 mm to 19 mm, an increase of the horizontal stiffness of the panel was observed (Fig. 10). However, the difference in stiffnesses did only vary significantly between 2 mm and 8 mm, with a maximum reduction of 14.5 % in case of a C100x1.5 section compared to the reference panel. Between glass thicknesses of 8 mm and 19 mm the variation was maximum 1 %. The influence of the glass thickness on the relative displacements between the glass panes and the CFS frame members was more significant. Increasing this thickness resulted in an increase of these relative displacements, hence less composite behaviour was observed. The influence of the adhesive thickness and the section thickness were more profound, although in case of a true optimisation, this parameter has to be taken into account, in particular for small glass thicknesses.

*4.5. Influence of section height and section width*

Increasing the section height (and therefore the thickness of the panel) from 100 mm to 150 mm by considering a C150 section instead of a C100 section, caused only an increase of 2.7 % in lateral stiffness compared to the reference panel (Fig. 10). The relative displacements between glass panes and frame increased with only 1.7 %, hence the influence on the horizontal stiffness was more significant. Important to notice is that a direct comparison between a C80 section and a C100 or C150 section is more difficult as the width of these sections, hence also the adhesive width for this investigation, is different. However, it does appear that the adhesive width is more important in the determination of the lateral stiffness than of the relative displacements between glass panes and frame (Fig. 10).

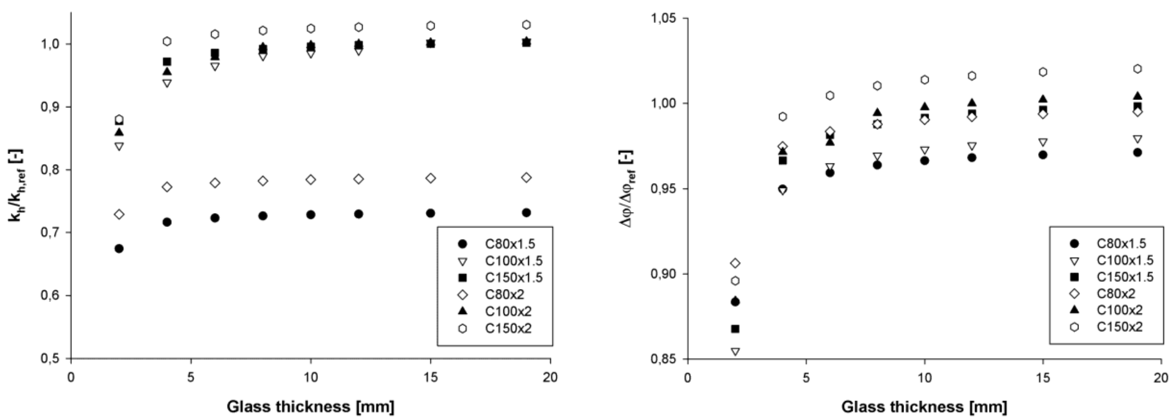


Figure 10: Influence of glass thickness and section type on lateral stiffness (left) and relative displacements between glass pane and frame (right)

## 5. Discussion

A true optimisation in terms of maximum lateral stiffness and maximum composite behaviour of the hybrid CFS-glass SWP is possible by taking into account the parameters investigated in this research, even though not all factors are equally significant or contributing.

As depicted in Fig. 7, the largest horizontal stiffness of the panel is obtained for large width-to-height ratios. In that case, however, the relative displacements between the CFS frame and the glass panes are very large (Fig. 7). Comparing a ratio equal to 1 to a ratio equal to 4 reveals a doubling of the horizontal stiffness, whilst the relative displacements increase by a factor of eight. This causes large deformations of the intermediate adhesive layer and thus the composite behaviour of the hybrid CFS-glass panel becomes less significant. To make this adhesive connection able to absorb and transfer these deformations and corresponding stresses, its material properties have to be well selected and its geometrical characteristics well designed. To improve composite behaviour, and thus to make the hybrid panel act as a whole, these relative deformations between the glass panes and the frame have to be reduced. This is possible by reducing the width-to-height ratio, which, however, results in a significantly smaller horizontal stiffness of the panel.

Configurations with considerable lateral stiffness and significant composite behaviour are the panels with reduced adhesive thickness (less or equal to 4 mm). When increasing the adhesive thickness (equal or greater than 8 mm), the joint becomes too flexible resulting in a reduced lateral stiffness combined with limited composite behaviour (Fig. 8).

However, a few remarks have to be made regarding this adhesive thickness. First, the current building codes on structural sealant glazing systems instruct a minimum thickness of 6 mm for the thickness of the structural silicone that is used (EOTA 2005), making smaller thickness not yet possible in practice. Moreover, the adhesive itself has to be gap-filling as the CFS tracks overlap the CFS studs creating additional tolerances, hence not all adhesives are suitable for this application. Furthermore, minimising the adhesive thickness to maximise horizontal stiffness and to minimise relative displacements between glass and frame has its limitations. The adhesive connection has to ensure a reliable transfer of occurring loads and, moreover, the absorption of constraining forces, such as thermal forces. Generally, for given design conditions, the overall geometric design of the adhesive layer has to be done such that all imposed requirements regarding available lateral stiffness, relative displacements and load transfers are met.

The thickness of the sections used as frame members has a greater influence on the resulting horizontal stiffness than on the composite behaviour (Fig. 9). Hence, the decrease in lateral stiffness of the hybrid CFS-glass panel by decreasing the section thickness is not compensated by significantly smaller relative displacements between the glazing and the frame. Moreover, the height of the CFS section, equal to the thickness of the panel, is also a parameter that has to be taken into account (Fig. 10). In case of the same section thickness, an increase in section height, resulted in an increase of the horizontal stiffness of the panel, but in a decrease of composite behaviour. The significance of this influence parameter on both lateral stiffness and relative displacement of glass panes and frame will be different than the significance of the section thickness. Hence, for the optimisation of the section of the frame members, the section thickness as well as the section height have to be considered. In this study, also the section width is of utmost importance as this section width is taken equal to the width of the adhesive layer between the glass panes and the CFS frame. An increase in this width resulted in an increase of the lateral stiffness (compare C80 with C100 or C150), however, the effect on the composite behaviour was less profound, suggesting therefore the possibility of a further optimisation of the geometrical characteristics of the adhesive layer.

Eventually, the thickness of the glass panes within a range of 2 mm to 6 mm will also determine the lateral stiffness and relative displacements between glass panes and CFS frame. Hence, when thicker glass panes are desired, the optimisation of the hybrid glass-CFS panel should focus on the geometrical design of the frame members for the considered adhesive joint. However, the influence of the glass thickness might become more profound, when adapting the geometrical properties of the adhesive layer, especially the width. Nevertheless, when comparing a C80 section with a C100 or C150 section, it seems that this parameter has rather limited influence, although it has to be noticed that a C80 section cannot be fully compared to a C100 or C150 section, because of the difference in section width. Still, it is to be expected that the influence of the glass thickness will become more important in case of further reduced adhesive widths, as the load transfers occur over smaller areas.

Using Fig. 11, deduced from Fig. 10 by combining both graphs, the optimal configuration for this numerical investigation can be derived. Both, adequate stiffness and acceptable relative displacements can be obtained by a configuration using C100x1.5, C100x2, C150x1.5 or C150x2 sections for the framing members and glass panes with a minimum thickness of 6 mm. Further optimisation for given design conditions (e.g. width-to-height ratio and glass thickness) is possible by optimising the geometry of the adhesive connection between the glass panes and the CFS frame (e.g. width, two –sided connection instead of circumferentially, etc.).

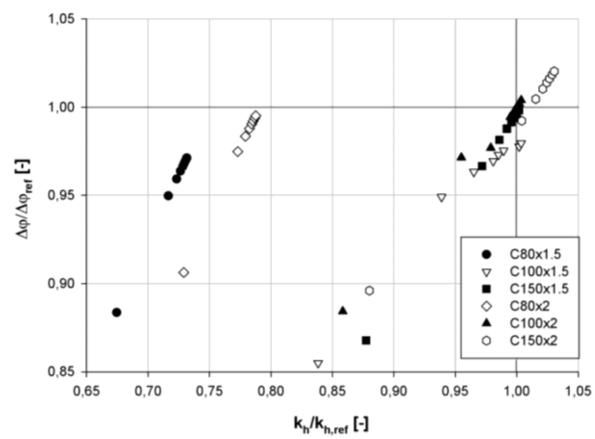


Figure 11: Relative displacements versus lateral thickness for the investigated configurations

## 6. Conclusions and further research

Based on a study of former experimental, numerical and analytical research of traditional cold-formed steel shear wall panels, an overview of the influence parameters on the behaviour of these type of structures was given. Six basic factors, differentiated in several parameters, were identified. Subsequently, this scheme was adapted to define the possible influence parameters on the structural behaviour of the newly developed concept of a cold-formed steel shear wall panel braced with adhesively attached glass panes. By means of numerical modelling, the significance of some of these parameters was investigated.

The width-to-height ratio of the hybrid CFS-glass panel had the most significant influence on its horizontal stiffness and its composite behaviour. Although an increase of this ratio resulted in an increase of the horizontal stiffness, it could not compensate the excessive increase in relative displacements between the glass panes and the frame. Increasing the adhesive thickness caused a decrease in lateral stiffness and a decrease in composite behaviour, whilst an increase in section thickness, section height and section width resulted in an increase in horizontal stiffness and relative displacements between glass panes and frame. However, these parameters were less significant than the adhesive thickness. Lastly, glass thickness is an important factor to take into account if it has a value below 6 mm.

To find the optimum configuration for given design conditions, all investigated influence factors have to be taken into account, even though their significance varies. In this study, the considered reference configuration already combines adequate lateral stiffness with satisfactory composite behaviour, compared to the other geometries considered. It is important to notice that for given design conditions, the overall behaviour of the panel can still be optimised by ensuring a reliable load transfer between the frame and the glazing, which can be done by optimising the geometry of the adhesive joint.

In further research, the influence of other parameters on the behaviour of hybrid CFS-glass panels can be investigated. This can be done either numerically or experimentally. To obtain the most reliable results, it is recommended to perform experimental tests on different configurations, so a numerical model can be validated. Then, this model can be used to perform extensive parametric studies to determine the significance of the influence of the parameters on the structural behaviour of the hybrid CFS-glass shear wall panels. From this, the optimal configuration for given design conditions can be determined. Furthermore, an analytical method, which probably could be based on existing methods for sheeted wood shear walls or traditional CFSSWPs, can be developed to determine the behaviour of these type of structures.

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