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# INFLUENCE OF CONTACT STRESS BETWEEN SHEETS ON STRENGTH AND STIFFNESS OF TIMBER FRAME SHEAR WALLS

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**ABSTRACT:** Sheathed light-frame timber shear walls are often used to stabilize timber buildings, protecting them from the effects of wind loads in particular. The analysis models used for such walls often neglects the contact forces between the sheets. In partially anchored shear walls, especially, these contact forces can become significant. In the present study, which only comprises walls without openings, the effect of these contact forces is evaluated for different loading and geometrical conditions using the finite element method. The analyses show that the internal force distribution in the wall is significantly affected by taking the contact forces into account. However, with respect to the load-carrying capacity of the wall, these contact forces have only a slight effect. The main reason for this fact is that the contact forces between the sheets can be replaced by forces transferred via the sheathing-to-framing joints along the top rail and to some extent also by forces transferred via the sheathing-to-framing joints along the upper parts of the vertical studs joining the different sheets.

**KEYWORDS:** Shear wall, Contact stress, Finite element analysis

## 1 INTRODUCTION

Timber-frame shear walls are commonly used in buildings to provide lateral bracing, protecting these houses from the effects of horizontal loads, such as wind loads. Many approaches for the analyses of the behaviour of such walls are available. Some researchers employ an analytical approach, see e.g. Källsner and Girhammar [1, 2], and others make use of the finite element method, e.g. Dolan and Foschi [3] and Folz and Filiatrault [4]. Shear walls have also been studied experimentally, see Seaders, Gupta and Miller [5], for example, who compared the behaviour of fully anchored walls with that of partially anchored shear walls.

In order to avoid excessive computational time when analyzing these walls numerically, it is expedient to employ relatively simple models. But those aspects need to be balanced in comparison to the accuracy of the model. A common simplification in the modelling of shear walls is to assume hinged joints between the framing members. This assumption corresponds to so-called fully anchored shear walls and requires the use of hold-downs to be fulfilled; see Källsner and Girhammar [2]. Another frequent simplification is to neglect the effects of contact forces transmitted between the sheets on the framing members of the shear wall. However, some studies have been conducted where the effect of contact forces has been taken into consideration; see e.g. Dolan and Foschi [3] and White and Dolan [6]. In both these studies a bilinear relationship was used for simulating the contact forces.

Although contact forces have been included in a number of models, the effects of these on the internal force distribution in and the load-displacement relationships for such walls have not been investigated thoroughly. The aim of the present study is to investigate the effects of assuming contact forces between adjacent sheets in both fully and partially anchored timber-frame shear walls. In fully anchored shear walls, the leading stud is tied down to prevent vertical uplift and in partially anchored shear walls the bottom rail is anchored to the foundation. These effects will be studied by using the finite element method.

## 2 GEOMETRY OF THE SHEAR WALLS STUDIED

A typical segment in a shear wall comprised of timber framing members, i.e. vertical studs and horizontal top and bottom rails, and the sheathing or sheets attached to the frame by mechanical fasteners is shown in Figure 1. The designations of the different members and parts of the segment are given in the figure. In case of more than one segment, the two adjacent sheets in the wall are attached to the same stud. The segments or sheets are numbered from the windward side.

In the present study, the dimensions of the framing members are 45×120 mm$^2$ (C24), and of the 8 mm thick hardboard sheets 1.2 m × 2.4 m (HB.HLA2, C40, Masonite AB). The sheathing-to-framing joints are

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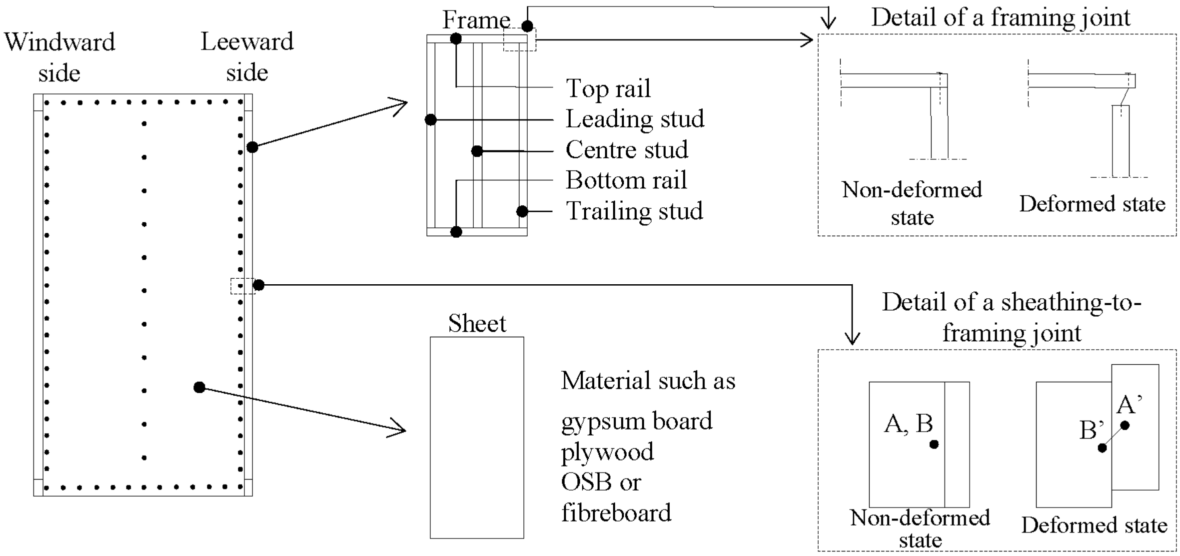


***Figure 1:*** *Structural components of a shear wall segment. The term leading and trailing stud apply to the first and the last stud in a shear wall. The location of the fastener in the sheet (B) and in the framing member (A) before and after the displacement and deformation of the system (in the non-deformed and deformed state, respectively) is shown in the lower right corner of the figure.*

formed by annular ringed shank nails of dimension 50 × 2.1 mm (Duofast, Nordisk Kartro AB) and the framing joints by two annular ringed shank nails of dimension 90×3.1 mm applied in the grain direction of the vertical studs.

# 3 FE MODEL OF THE SHEAR WALL

## 3.1 MODEL GEOMETRY

Finite element simulations were performed using the commercial software Abaqus. The timber members and the hardboard sheets are assumed to have linear elastic properties. Second-order beam elements with a cross-section of 45×120 $mm^2$ are used to model the framing elements (with a modulus of elasticity, $E$ = 12 GPa and a shear modulus $G$ = 750 MPa). The sheets are modelled using four-node linear plane stress elements (with $E$ = 6 GPa and G = 2.3 GPa).

To be able to use beam elements for modelling of several shear wall segments placed side by side, the rows of fasteners along the joining studs are moved to the vertical edges of each sheet so that the two rows of fasteners coincide in the middle of the joining stud. This implies that the actual distance of 22.5 mm between the two rows of fasteners is reduced to zero in the model, which results in roughly a 2 % overestimation of the strength of the shear wall. The simplicity of this approach, in which the periphery of the sheets coincides with the centre lines of the studs, motivates use of the approximation involved. It should be borne in mind however, that using this approximation results in the capacity of the wall being somewhat overestimated.

The fasteners near the peripheral edge of the sheet are at a distance of 100 mm apart, whereas those in the centre stud are 200 mm apart.

## 3.2 MODELS OF THE JOINTS

### 3.2.1 Sheathing-to-framing joints

It is well known that the properties of the separate sheathing-to-framing joints are decisive for the properties of the shear wall. In the present study, a single-spring model is used for modelling this important connection, for further details see e.g. Judd and Fonseca [7]. The use of this model implies that only one load-displacement curve applies to each of the fasteners. In analyzing the shear wall as a whole, the applicability of four different load-displacement curves is explored, see Figure 2. Two of these are based on experiments performed in the parallel and the perpendicular direction, respectively, relative to the timber member; see Girhammar, Bovim and Källsner [8].

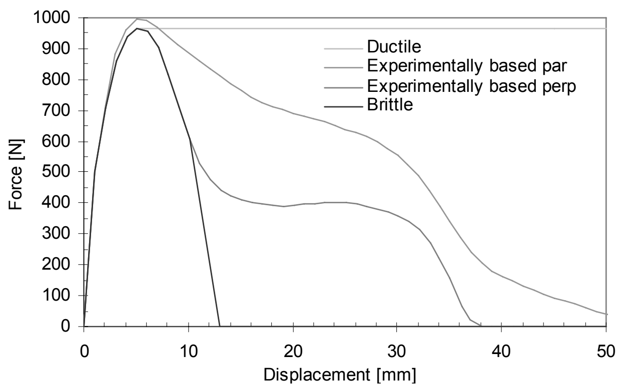


***Figure 2:*** *Four different load-displacement curves for the sheathing-to-framing joints, termed (a) ductile, (b) parallel, (c) perpendicular, and (d) brittle characteristics. (b) and (c) are experimentally based, and (a) and (d) are chosen to represent the extreme cases.*

The other two curves that are included in the analysis, a ductile and a brittle one, represent two extremes in regard to the performance of the joint. In case of unloading of a joint, a plastic linear unloading path is assumed (parallel to the initial stiffness). The parallel characteristics (b) are used in the simulations, except where indicated otherwise.

### 3.2.2 Framing joints

Adjacent wall segments share the intermediate stud between them and they have the top and bottom rails in common. The framing joints are very important in analysing the performance of the shear wall with respect to shearing, compression and tension. In many models, the framing joints are modelled as frictionless hinges, not allowing for any horizontal translation, uplift or plastic compression; see for example the analytical model of Källsner and Girhammar [2] and the finite element model of Collins et al. [9]. The different properties of the framing joints assumed in this study are shown in Figure 3 as piecewise linear relations. These estimates are based on experimental results performed by Palm [10]. No rotational stiffness of the joint is assumed.
In the finite element model, these characteristics in shear, compression and tension are assumed to be uncoupled.

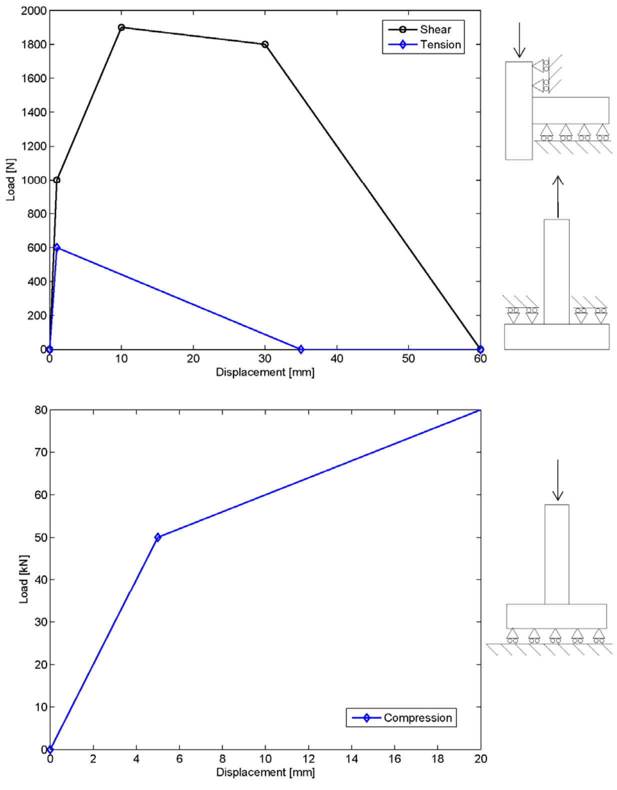


***Figure 3:*** *Properties assumed for the framing joints in the horizontal direction (shear) and the vertical direction (tension and compression).*

## 3.3 MODELS FOR THE CONTACT BETWEEN ADJACENT SHEETS

The possible contact between adjacent sheets is modelled as forces perpendicular to the two surfaces in the vertical interlayer between them. Hard contact is assumed, implying that no penetration of one surface into the other can occur. Lagrangian multipliers are used to impose this constraint, enabling a possible separation of the two surfaces without restriction after they have been in contact.
The contact forces discussed here are the sum of the forces developed in the entire area where the two sheets are in contact. The initial gap between the sheets is assumed to be zero. The results of models with and without contact will be compared.

## 3.4 LOAD CASES AND SUPPORT CONDITIONS

Shear walls with three different geometrical configurations (including one, two and three segments) subjected to two different loading conditions (diagonal and horizontal loading), are analysed, see Figure 4. In all cases, only the bottom rail is anchored to the foundation and all other properties are the same. The case of diagonal loading corresponds to a fully anchored shear wall (for which the highest possible capacity is attained) and that with horizontal loading will represent a partially anchored shear wall, see Källsner and Girhammar [1, 2]. It is noted that in the diagonal case, only the leading stud acts as fully anchored. In an ideally fully anchored shear wall, the sheets rotate the same amount and, therefore, no contact forces develop between them and no uplift or translation takes place at the stud-rail intersection point (the framing joints behave as hinges). These conditions are not fully met in shear walls subjected to diagonal loading.

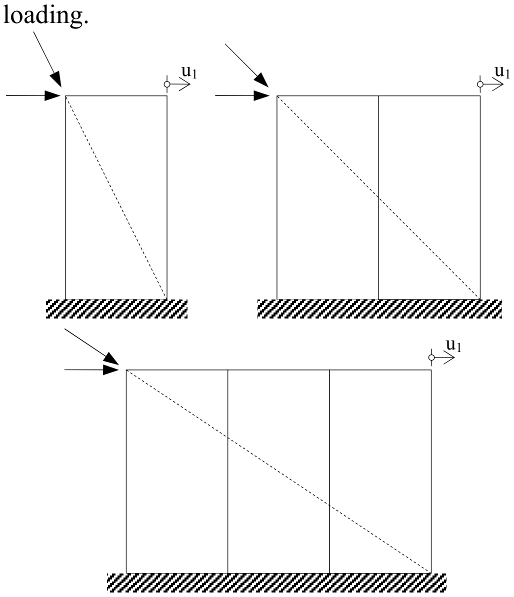


***Figure 4:*** *Three geometrical configurations including one, two and three segments and two loading conditions, diagonal and horizontal loading, for the analysed shear walls. The horizontal displacement is measured at the top rail. The two different loading directions correspond to fully and partially anchored shear walls, respectively.*

When load-displacement curves for the shear walls are analyzed, the horizontal component of the load is plotted against the horizontal translation of the top rail. All loading is applied by means of displacement control so that the post-peak behaviour of the walls can be followed.

# 4 RESULTS

## 4.1 CONTACT FORCES BETWEEN ADJACENT SHEETS

Figure 5 shows load-displacement curves for fully and partially anchored shear walls comprising one, two or three segments, and modelled with and without contact between the sheets. The fully and partially anchored shear walls with a single segment are included for reference purposes. It is evident from the figure that there is a the large difference between the capacities of fully anchored shear walls compared to partially anchored ones, but also the small difference between cases with and without contact.

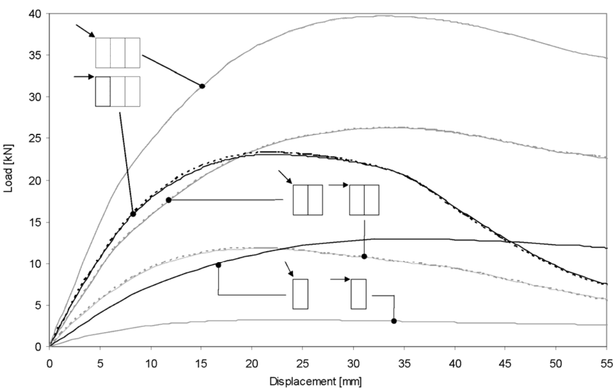


***Figure 5:*** *Load-displacement curves for fully and partially anchored shear walls comprising one, two and three wall segments, with and without contact between adjacent sheets. Shear walls with a single segment are shown for reference purposes.*

The horizontal contact forces that develop between the sheets are shown in Figure 6 as a function of the horizontal displacement of the top rail. As expected, the contact forces are much higher in partially anchored shear walls than in fully anchored ones. The largest contact forces, of a magnitude of nearly 6 kN, are those between the first and second sheet in the partially anchored shear wall with three segments, whereas the smallest maximum values, of a magnitude of less than 1 kN, occur in the fully anchored shear walls. This difference can be explained by the different behaviour of fully and partially anchored shear walls, especially in the area of the leading stud. In fully anchored shear walls the sheets rotate (almost) the same in all segments and no essential contact forces develop (the shear forces in the sheathing-to-framing joints tend to be directed parallel to the framing members around the segment). In a partially anchored shear wall, however, there is uplift of the leading stud and the shear forces in the sheathing-to-framing joints along the bottom rail are almost perpendicular to the rail. This effect of the uplift is of course most pronounced in the segments closest to the leading stud and decreases away from that area. The different sheets then rotate to different degrees and, therefore, contact forces develop between them.

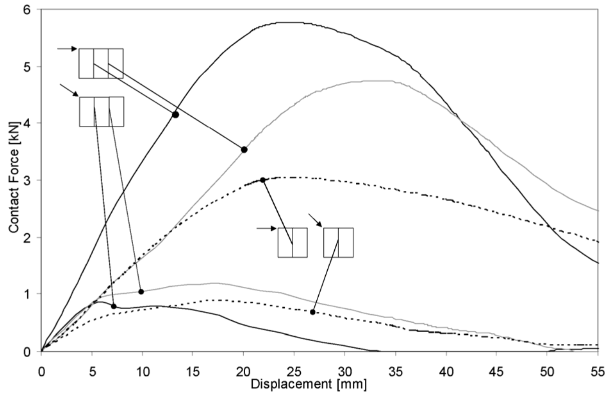


***Figure 6:*** *Contact forces between the sheets in shear walls with two and three segments, respectively, plotted versus the horizontal displacement of the top rail.*

The distribution of the contact stress between the sheets is shown in Figure 7 for the different cases; the contact stresses along the height of the shear wall are depicted at the instance of maximum load on each wall according to Figure 5.

As is evident from Figure 7, the contact stresses are transmitted near the top of the sheet in case of partially anchored shear walls, but in the lower parts of the sheets in case of fully anchored ones. The small contact stresses that develop in the fully anchored cases in Figure 7 can be explained by local deformations in the framing joints.

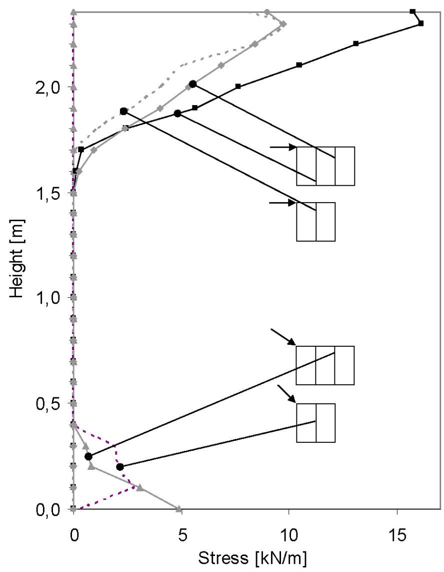


***Figure 7:*** *The profile of contact stress between adjacent sheets at maximum capacity for each load case.*

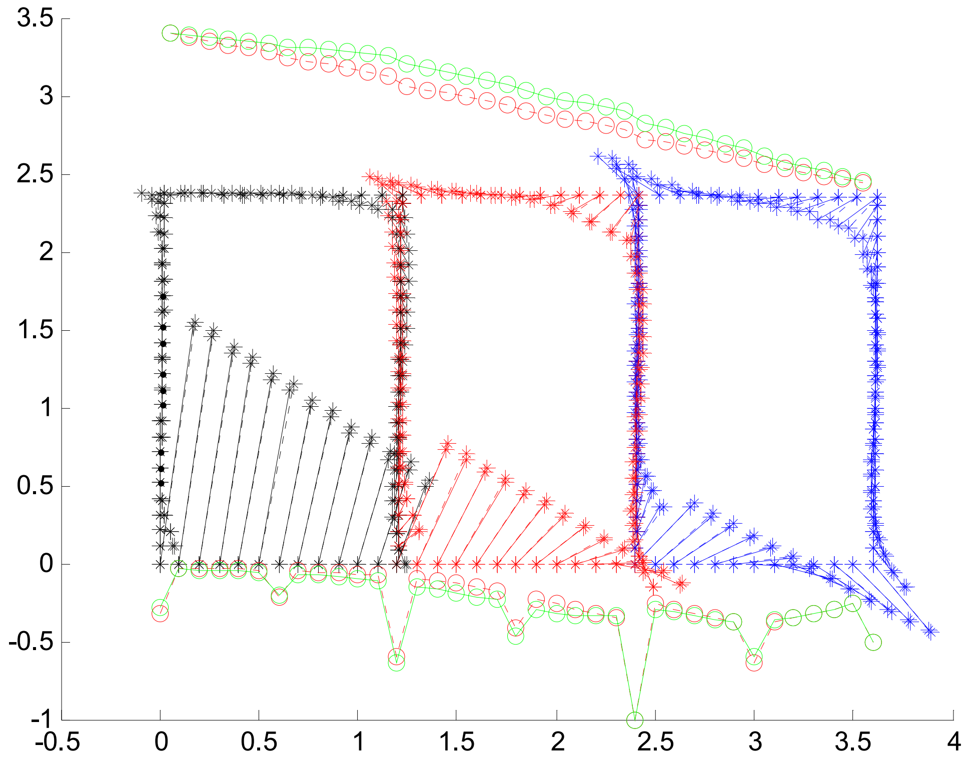


***Figure 8:*** *Scaled displacements of fasteners in a partially anchored shear wall with three segments at the instance of maximum load in case of contact (dashed lines) or no contact (solid lines) between adjacent sheets. Also, the normal force in the top rail and the horizontal component of the distributed reaction force along the bottom rail are plotted for the two contact cases (normalized with respect to their maximum values).*

### 4.2 DISPLACEMENT OF FASTENERS AND NORMAL FORCE IN RAILS

According to Figure 5, the load-displacement curves for the different cases are essentially the same, whether or not contact forces are included in the analysis. This is valid in spite of the fact that the magnitude of the contact forces can be as high as one fourth of the maximum load capacity of the shear wall, cf. Figure 6. It is of interest, therefore, to investigate further the effect of the contact forces on the force distribution along the top and bottom rails, and on the forces in the individual joints.

As an example, the displacements of the fasteners at the instance of the maximum load for the partially anchored shear wall with three segments, are shown in Figure 8 (scaled 100 times) for both cases of contact (dashed lines) and no contact (solid lines). Also, the normal force in the top rail and the horizontal component of the distributed reaction force along the bottom rail are shown in the figure (normalized with respect to their maximum values).

The largest displacement of a fastener occurs at the lower left corner of the first sheet. Especially in the first segment, this displacement takes place almost in the vertical direction.

A detailed study shows that a large difference between the effect of contact and no contact is found for the fasteners along the top rail of the first sheet, where the horizontal translational component is larger when contact forces are included in the model. This means that a larger horizontal force is transferred from the first sheet to the top rail when contact is assumed. It is also observed in Figure 8 that the normal force in the top rail is distributed more linearly when contact forces are assumed in the analysis. The horizontal component of the distributed reaction force along the bottom rail does not differ much in the two cases of contact or no contact. The peak values noted at the stud-to-rail intersections are due to the local forces assumed in the framing joints according to Figure 3.

However, the load-carrying capacity of the shear wall is to a large extent determined by the holding down capacity of the fasteners connecting the sheets to the bottom rail. Since the behaviour of the fasteners is essentially the same in this respect according to Figure 8, the overall behaviour and load-carrying capacity of the shear wall also are the same, with or without contact.

### 4.3 BEHAVIOUR OF SHEAR WALLS DUE TO DIFFERING CHARACTERISTICS OF THE SHEATHING-TO-FRAMING JOINTS

The load-displacement curves for a partially anchored three segment shear wall are shown in Figure 9. The curves are based on the four different characteristics of the sheathing-to-framing joints presented in Figure 2 and on the assumption of contact or no contact between the sheets. As expected, the highest load-carrying capacity is attained when the joint characteristics are ductile. This is true even if the maximum strength of the individual sheathing-to-framing joint is larger as in case of parallel characteristics according to Figure 2. The reason for this is that in the ductile case a greater number of fasteners act at maximum capacity in holding down the shear wall. In the other cases, some joints have not yet reached the maximum strength and some have passed it at the instance of maximum capacity of the shear wall. It is obvious from Figure 9 that the peak value of the curves (b)–(d) in Figure 2 cannot be used in a rigid plastic analysis. For approximately the same peak values of the curves in Figure 2, the load-carrying capacity of the shear wall varies from 20.8 kN (brittle) to 25.5 kN (ductile).

It is noted in Figure 9 that in all cases the maximum load is slightly higher in the case of contact than of non-contact. The maximum difference at maximum load is less than 1.5 %.

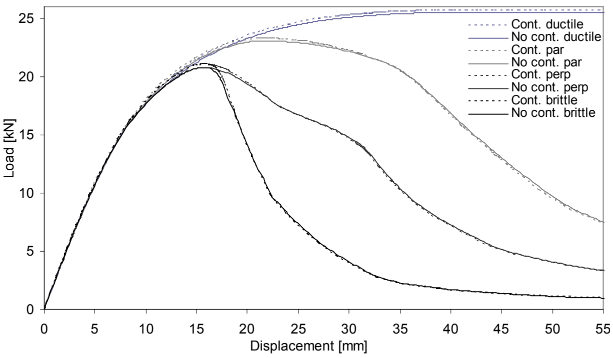


***Figure 9:*** *Load-displacement curves for partially anchored three segment shear walls with (dashed lines) and without contact (solid lines) between the adjacent sheets. The curves are based on the sheathing-to-framing joint characteristics shown in Figure 2.*

## 5 CONCLUSIONS

Fully and partially anchored shear walls were modelled using the finite element method to evaluate the effects of contact between adjacent sheets. Four different load-displacement curves were used for the sheathing-to-framing joints ranging from brittle to ductile behaviour. As expected, in fully anchored shear walls the influence of contact between the sheets is negligible, but in partially anchored shear walls the contact forces can become significant.

The influence of these contact forces were shown to be significant with respect to the internal force distribution, but negligible with respect to the load-displacement relationships and the load-carrying capacity. Therefore, when determining the load-carrying capacity of shear walls of the type studied it seems reasonable to neglect the influence of contact forces between sheets.

The reason for the insignificant influence of the contact forces on the overall behaviour of the shear walls studied is mainly that the contact forces between the sheets will be transmitted in other ways if they are not included in the analysis, namely via the sheathing-to-framing joints along the top rail and to some extent also via the sheathing-to-framing joints along the upper parts of the vertical studs joining the different sheets.

A consequence of this is that the force distribution in the sheathing-to-framing joints along the bottom rail will not be much affected if contact is assumed or not.

The study also shows that the load-displacement curves of shear walls differ considerably depending on the degree of ductile behaviour of the sheathing-to-framing joints. This result is of decisive importance with respect to the determination of the design value for the sheathing-to-framing joints in a rigid plastic analysis of the load-carrying capacity of shear walls.

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