NUMERICAL STUDY OF TIE FORCE DISTRIBUTION IN VENEER WALL SYSTEMS

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ABSTRACT

In veneer wall construction, the wall ties play an important role in supporting the veneer and transferring the face loads from wind or earthquakes to the backup wall. Wind pressure or suction and seismic loads result in both tensile and compressive forces in ties. The evaluation of the tie force has been traditionally based on tributary area, which results in prescriptive limits on tie spacing. However, some studies have shown that the distribution of forces in the ties is dependent on a range of factors and tributary area based distribution certainly does not reflect the true force in the ties.

The current Canadian masonry design standard prescribe that for a flexible backing, each tie be designed using a load equal to 40% of the tributary lateral load on a vertical line of ties. The rationale for 40% tributary load was based on elastic analysis assuming the tie infinitely rigid in tension and compression.

This paper presents a finite element study on the distribution of tie forces in veneer wall systems. Parameters considered include support conditions for veneer and back-up walls, load application being either pressure or suction, stiffness ratio of the veneer and backup walls, and stiffness and spacing of ties. The effects of these parameters on the tie force distribution are presented. The redistribution of tie force after tie buckling is also studied. The adequacy of 40% rule specified by the Canadian standard is discussed.

KEYWORDS: veneer wall, tie load, tie stiffness, flexible backup wall, Canadian masonry standard, numerical study

INTRODUCTION

In modern masonry construction, masonry veneer walls are commonly used as the exterior facing to complete the building envelope. They are usually anchored to a structural back-up wall using a series of metal ties. Often, the structural back-up wall is provided by either masonry wall or timber/steel frame systems. Although the masonry veneer is not relied upon to contribute to the structural performance of the wall, it must be able to carry its own weight and transfer face loads from wind or earthquakes, through the ties to the back-up wall. Wind pressure or suction and seismic loads result in both tensile and compressive forces in ties. The design tie force has been traditionally based on tributary area, which results in prescriptive limits on tie spacing specified in many current design standards. This practice is based on the assumption that all ties develop equal forces, which would be the case if the inner and outer wythes experience the same rigid body movement [1]. However, a realistic veneer wall system will deflect and the deflection characteristics will be different for different back-up systems. The previous research [2, 3, 4] has shown that the distribution of tie forces depends on the rigidities of the veneer and back-up walls, wall support conditions, and tie stiffness and location. For the case of stiff ties with stiff backup walls, the tie force distribution is relatively uniform and the tributary area approach may be acceptable. As the backup wall becomes more flexible, the tie force prescribed based on tributary area does not reflect the actual distribution of forces. Furthermore, analytical studies considering the cracking of veneer and backup masonry [5, 6] indicated that cracking can change the tie force distribution significantly. Whether the cracking is considered or not, the use of tributary area approach does not reflect the actual tie force distribution and in some cases, may actually underestimate the force that can develop in ties.

The current Canadian masonry design standard CSA S304 [7] prescribes that for a flexible backing, each tie be designed using a load equal to 40% of the tributary lateral load on a vertical line of ties, but not less than double the tributary lateral load on the tie. The flexible backing is defined as having a stiffness less than 2.5 times the stiffness of the veneer and steel stud back-up wall system falls into this category. This rule was based on elastic analysis assuming the tie infinitely rigid in tension and compression. The efficacy of this prescriptive limit needs further examination for various parameters that deemed influential in the tie force distribution. It is also useful to examine how the tie system redistributes the load if failure occurs on one tie. The objective of this study is then to investigate the tie force distribution as affected by several parameters in the veneer wall system using finite element modeling. The parameters considered include the support conditions, load direction, tie stiffness, tie spacing, and relative stiffness of veneer and back-up wall. The numerical results are used to assess the validity of the provisions specified in the CSA S304.

MODEL DESCRIPTION

A finite element model is developed in this study using software ANSYS. Figure 1 shows a schematic view of the model. Unless otherwise specified, the wall is modeled as 6.0 m high, the distance between ties is 600 mm, distances between the top tie to the top of the wall and the bottom tie to the bottom of the wall are 300 mm in both cases. For masonry ties commonly used in Canada, a reasonable range for stiffness is from 0.5 to 2.5 kN/mm. They are flexurally flexible enough so the coupling between wythes can be ignored, and thus the ties are modeled using truss element. Three ratios of backup wall to veneer stiffness, $EI_b/EI_v = 0.25, 1.0, 2.5_,$ were selected to represent a range of flexible back-up walls defined by CSA S304. The cracking in the veneer wall was modeled by introducing a hinge at that location. Both veneer and back-up walls are modeled using beam element.

Three cases of back up wall boundary conditions are considered as shown in Figure 1. In these cases, the back-up wall is assumed to be pin-supported on both the top and bottom (Case 1), fixed supported on the bottom and pinned on the top (Case 2), and pinned on the bottom and continuous on the top (Case 3).

TIE FORCE DISTRIBUTION - ELASTIC ANALYSIS

The tie force distribution based on the assumption that ties are infinitely rigid in tension and compression is presented in the following section. The load is applied as a uniform distributed pressure on the veneer wall and the positive tie force indicates the tie in compression.

Figure 2 shows the distribution of tie forces as affected by veneer to back-up wall stiffness ratio, EI_b/EI_v, for both uncracked and cracked situation. A tie stiffness of 2.5 kN/mm with Case 1 boundary condition was assumed in this study. As expected, for the support condition considered, the highest force occurs in the top tie among all ties. This force reached the maximum, equal to about 60% of the total load, when the backup wall is most flexible ($EI_b/EI_v=$ 0.25). The same analysis was carried out for a cracked veneer where a hinge was introduced at the mid-height of the veneer and the results are illustrated in Figure 3. A pronounced increase in force in ties adjacent to the mid-height was evident but the top tie remained to be the most stressed tie with a higher magnitude than the uncracked situation. Ties in the lower half and upper half of the wall developed marked tensile force about 40% of the total load. For both cracked and uncracked cases, the highest forces developed are higher than the 40% of the total load, the design value specified in the CSA S304.

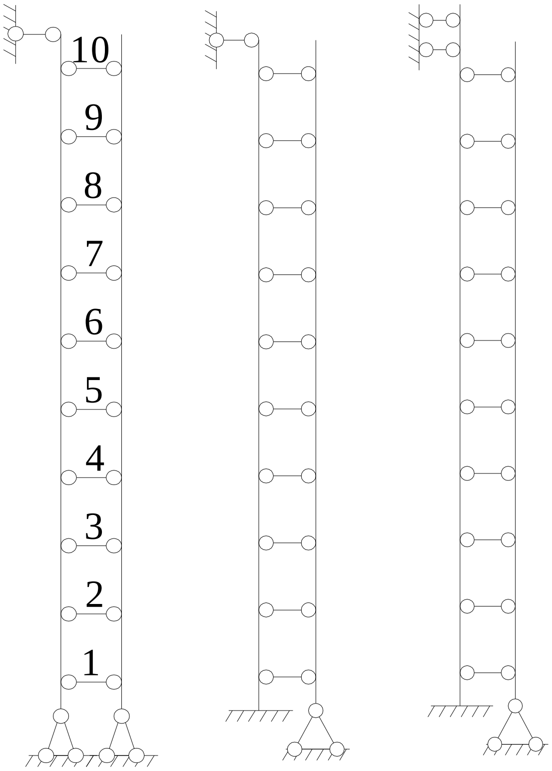


Figure 1: Veneer wall system model (a) Case 1, (b) Case 2, (c) Case 3

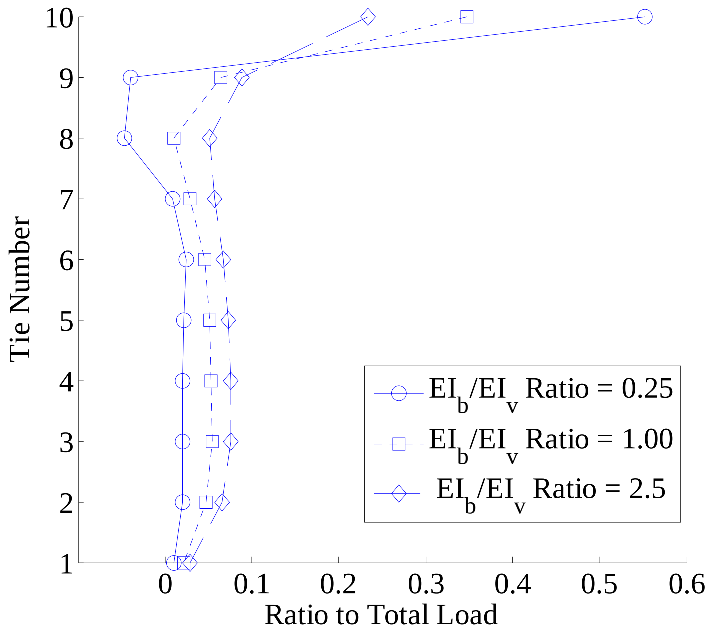


Figure 2: Tie force distribution for different EI_b/EI_v ratios (Case 1, uncracked)

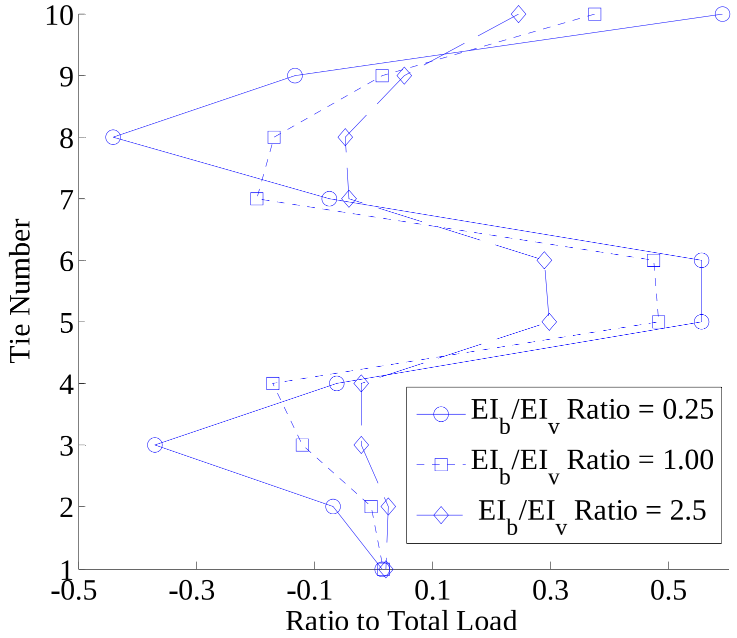
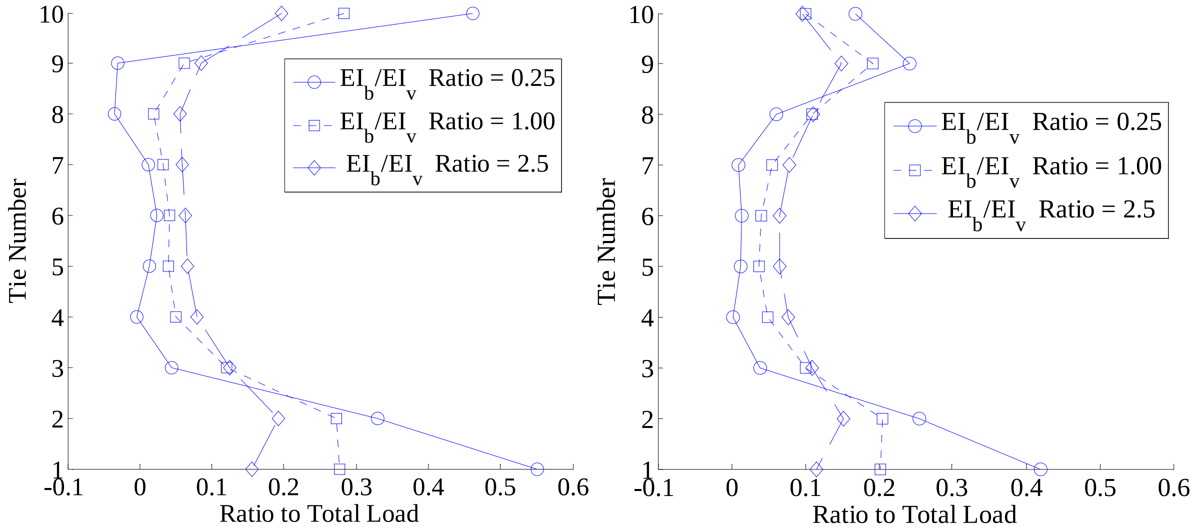


Figure 3: Tie force distribution for different EI_b/EI_v ratios (Case 1, cracked at mid-height)

SUPPORT CONDITION

Case 2 and 3 boundary conditions may also be encountered in practice and the tie force distributions for these 2 cases are shown in Figure 4 while other parameters are kept to be the same.



(a) Case 2 (b) Case 3

Figure 4: Tie force distribution for different boundary conditions

It can be seen that consistent with the discussion earlier, the most flexible backup wall resulted in the highest force distribution for three stiffness ratios considered. The change of bottom support of the backup wall from pinned to fixed changed the tie force distribution. While the top tie and second top tie still experienced large force, the bottom tie attained the highest force among all ties. The magnitude of the highest tie force for these support conditions is similar to that in Case 1 condition. It can be expected that the magnitude of the force in the cracked veneer would be similar to Case 1 as well. In all cases, the highest tie force developed is greater than the design value prescribed by CSA S304.

PRESSURE vs. SUCTION

Since most standards require the design for both pressure and suction acting on the veneer wall system, in this section wind pressure is applied as suction on the back up wall. It was assumed that the cavity was vented to the outer atmosphere that a pressure differential across the wall would result in suction applied on the surface of the backup wall. Figure 5 shows the tie distribution for Case 1 boundary condition while other parameters were kept the same. Comparing Figure 5 with Figure 1, the distribution trend is similar except that when the negative pressure is considered, the highest force developed at the top tie is tensile with slightly lower magnitude than that shown in Figure 1 but is still greater than 40% of the total load.

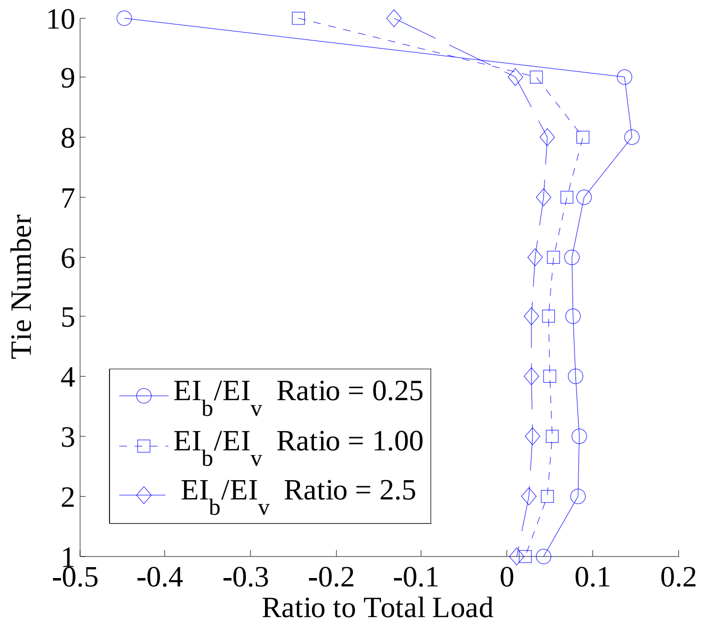


Figure 5: Tie force distribution for negative wind pressure

TIE SPACING

The tie force distribution as affected by tie spacing is shown in Figure 7 where three tie spacing, i.e. 300, 600, and 900 mm are considered. The tie stiffness is 2.5 kN/mm with a flexible backup wall ($EI_b/EI_v=0.25$) and the boundary condition is Case 1. It can be seen that the distribution along the height of the wall is similar for the three spacings and as expected, the tie force increases as the spacing increases. This increase is most significant at the top of the wall where the ties are most stressed. A spacing of 300 mm corresponded to a top tie force of 50% of the total load as opposed to 55% of the total load at the spacing of 600 mm. It seems to suggest that since the high force develops in a couple of ties close to support and the rest of ties are only marginally stressed. The reduction in spacing does not result in any significant reduction in the highest force.

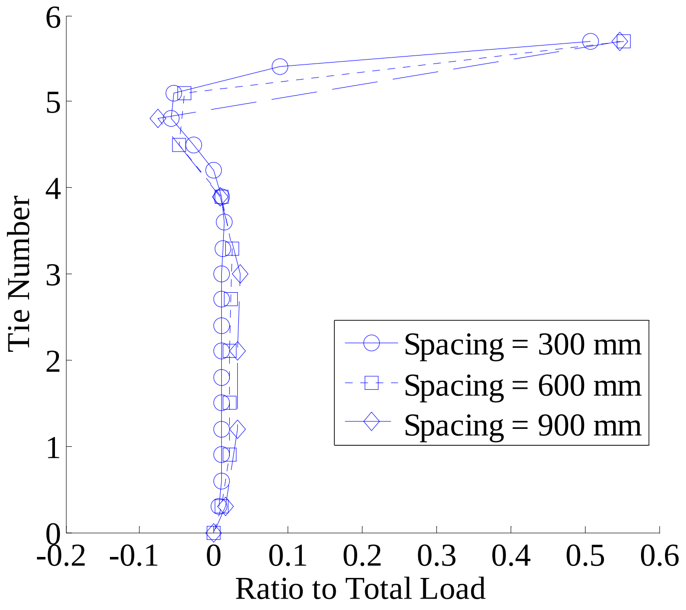


Figure 6: Tie force distribution for different tie spacing

TIE STIFFNESS

The tie force distribution as affected by tie stiffness is illustrated in Figure 7 where four tie stiffness, i.e. 0.5, 1, 2.5 and 10 kN/mm are considered. The Case 1 boundary condition with relative stiffness $EI_b/EI_v=0.25$ is used in this study. It is evident that the tie stiffness affects the distribution and the magnitude of the highest tie force. As the tie stiffness increased, the magnitude of force that developed in the most stressed tie increased. At tie stiffness equal to 10 kN/mm, the tie force attained is greater than 60% of the total load.

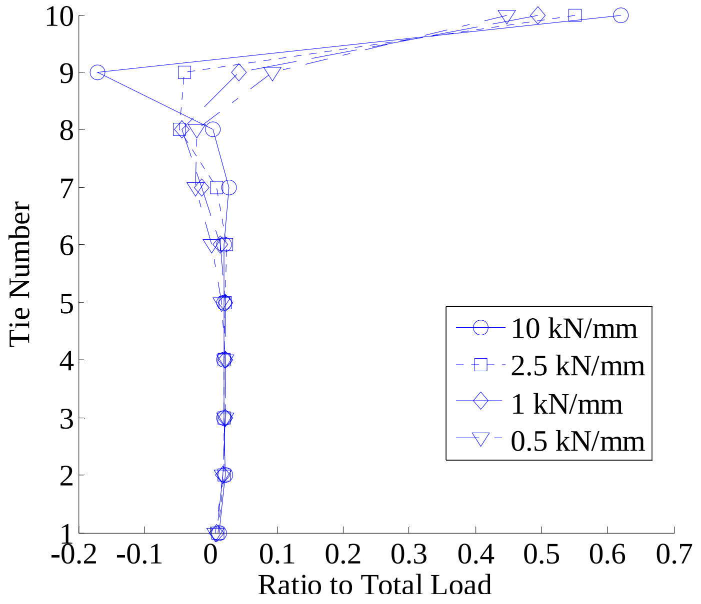


Figure 7: Tie force distribution for different tie stiffness

The above discussions show that the tie stiffness and EI_b/EI_v ratios are two major factors affecting the highest force that can be developed in ties. Figures 8 and 9 show the highest tie force as affected by the tie stiffness and EI_b/EI_v ratios respectively for Case 1 boundary condition. As shown in Figure 8, the increase in the magnitude of the highest tie force appears somewhat linear when the tie stiffness varied from 0.5 to 2.5 kN/mm. As the tie stiffness increased to 10 kN/mm, the rate of increase in the highest tie force decreased. Figure 9 shows that as the stiffness ratio EI_b/EI_v increased, the magnitude of the highest tie force decreased. At $EI_b/EI_v = 2.5$, the highest tie force that can be developed is between 20 to 30% of the total load. This load is less than the load based on the tributary area for one tie. It is therefore reasonable to assume that for EI_b/EI_v ratios greater than 2.5, the design tie force based on its tributary area is adequate. However, for flexible backup walls (EI_b/EI_v ratios < 2.5), it suggests that the "40% rule" specified by CSA S304 may not be adequate.

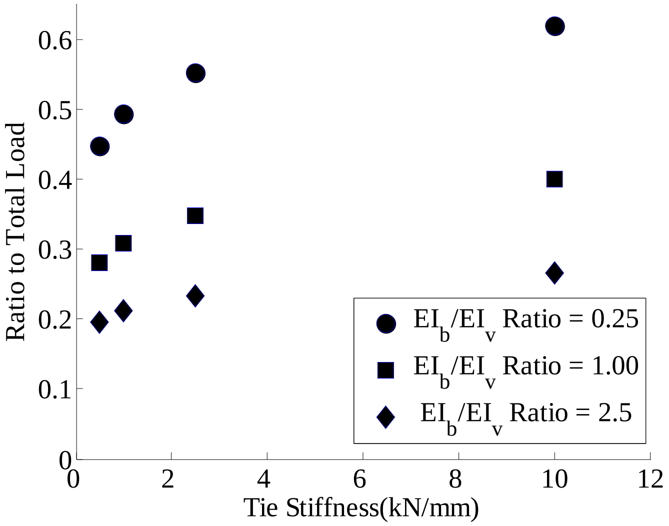


Figure 8: Effect of tie stiffness on the highest tie force

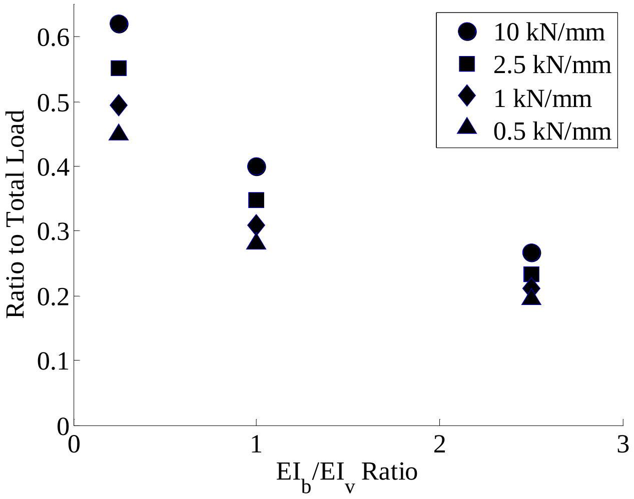


Figure 9: Effect of EI_b/EI_v on the highest tie force

TIE FORCE DISTRIBUTION – CONSIDERING TIE BUCKLING

The discussion earlier shows that the tie force distribution along height of the wall and the magnitude of the highest force are influenced by many factors. The most critical combination is rigid tie with flexible back-up wall in Case 2 boundary condition. In the case of cracked wall, the tie adjacent to the crack experiences a significant increase in force. Since the cracking location cannot be accurately predicted, each tie should be designed with the same prescribed load. The highest force that can be developed is greater than 40% of the total load. In the case of high walls, this load can be significant. For example, for a 6m high veneer wall subjected to 1 kPa wind pressure and 800 mm steel stud (back-up) spacing, the 40% of the total load along a vertical line of ties would be equal to 4.8 kN and this value will be used for design of each tie in this vertical line.

This section examines the force distribution after compression or tension failure occurs in one or more ties assuming that the veneer wall system has sufficient flexibility for a redistribution of forces among remaining ties. While a tension failure is commonly characterized by the tie pull-out, the compression failure is usually caused by the buckling of the tie. For the ease of discussion, it is assumed that the tie having the highest load buckles and is able to maintain 75% of its buckling strength to resist compression after buckling.

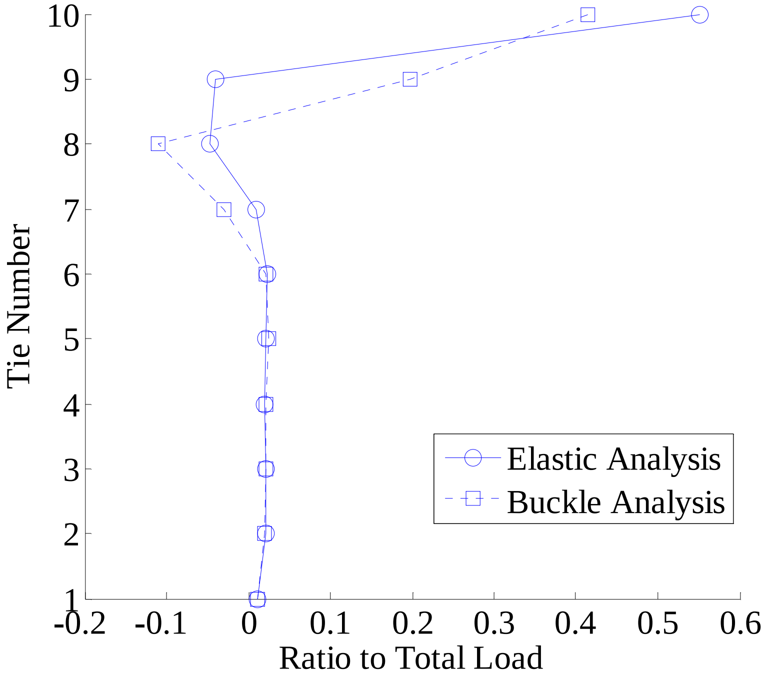


Figure 10: Tie force distribution considering a tie buckles

Figure 10 shows that the buckling of the top tie affected the tie distribution. After the top tie buckled, the ties 9, 8, and 7 experienced increases in load to various degrees while loads in ties 1 to 6 remained practically unchanged. The equilibrium is re-established. This suggests that the redistribution of the tie force is possible provided that the tie has reserve strength after buckling.

CONCLUSIONS

A numerical study based on finite element modeling is carried out to investigate the tie force distribution in veneer wall systems. Several factors are considered including the support condition, loading direction, tie spacing, tie stiffness and relative stiffness between the veneer and backup wall. Conclusions stemmed from this study are as follows.

1. Tie stiffness and relative stiffness of veneer and back-up wall are two main factors affecting the tie force distribution. The most critical combination is rigid tie with flexible backup wall which results in the largest tie force in the most stressed ties. For a given EI_b/EI_v ratio, the increase in the tie force as tie stiffness increases is somewhat linear for ties with common stiffness. For a given tie stiffness, the tie force increases as EI_b/EI_v ratio decreases.

2. The support conditions affect the tie force distribution. The change of backup wall bottom support from pinned to fixed shifted the highest tie force from the top tie to the bottom tie. The magnitude of the highest force is, however, similar.

3. The tie force showed a significant increase in ties adjacent to the crack in veneer and the magnitude of the force is in the same order as that in the most stressed tie in the uncracked situation.

4. The suction on the backup wall instead of pressure on veneer resulted in tension in ties with the magnitude of the highest force slightly less than the case when the pressure is applied.

5. For flexible back up wall ($EI_b/EI_v < 0.25$), the highest force that can be developed in ties is greater than 40% of the total load for all tie stiffness considered. It suggests that for flexible back up wall, caution should be exercised in applying “40% rule”, a load up to 60% of the total load may be expected in the most stressed ties. Two ties in that location may be necessary.

6. If the tie has reserve strength after buckling, a redistribution of tie forces may occur to achieve system equilibrium.

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