NUMERICAL INVESTIGATION OF THIN UNSTIFFENED STEEL PLATE SHEAR WALLS

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SUMMARY

A steel plate shear wall, resembling a cantilevered vertical plate girder is an effective lateral load resisting system for multi-storey buildings. The web plates are typically very slender and lateral loads are primarily carried by a diagonal tension field in combination with the frame action of the surrounding beams and columns. The Canadian Code on Limit States Design of Steel Structures, CAN/CSA-S16.1-94 (1994) recognizes this system and provides guidelines for analysis and design. A simplified strip model is proposed for use with conventional frame analysis programs

This paper reports on a numerical study using different strip models to compare with test results of two single storey and one four-storey specimens tested at the University of British Columbia. In general, the code prescribed strip models reasonably predicted the yield and ultimate strengths, but overpredicted the elastic stiffness of the test specimens. The load-deformation behaviour of the specimens was considerably affected by small variations of the angle of inclination of the tension strips representing tension field development. The discrepancies between the analytical and experimental results were more dramatic for the four-storey specimen, which was deemed to be a function of the overall aspect ratio (total height over panel width) of the specimen. An improved numerical model was proposed that utilizes discrete strips placed at different angles. The proposed model predictions showed improved correlation with the envelope of cyclic test results obtained from experimental studies at the University of British Columbia.

INTRODUCTION

In recent years the idea of utilizing the post-buckling strength of thin infill steel plates connected to a boundary frame as lateral load resisting system in multi-storey buildings has gained wide attention from researchers in Canada and the United States. A number of static and quasi-static cyclic tests performed on large and small scale models have been reported since 1983. These studies have examined the behaviour of steel plates throughout the entire range of loading, from elastic to plastic and from pre-buckling to post-buckling stages. The results unanimously support the rationale of using the post-buckling strength (or tension field action) and the stable energy absorption capacity of the steel panels in designing the primary lateral load resisting system for buildings.

In the early 1980's, the idea of utilizing the post-buckling strength of infill shear plates was introduced by researchers at the University of Alberta, who conducted extensive experimental and theoretical studies of the quasi-static cyclic behaviour of unstiffened steel plate shear wall panels. Consequently, an appendix describing a simplified approach for the analysis and design of thin unstiffened steel plate shear walls was introduced in the latest version of the Canadian Code on Limit States Design of Steel Structures, CAN/CSA-S16.1-94 (1994), contains. These guidelines are primarily based on an analytical model developed by Thorburn et al. (1983), which has been substantiated by experimental tests of two single storey shear wall panels utilizing fixed and pinned beam-to-column connections (Timler and Kulak, 1983) or standard bolted shear-type connections at the beam-to-column joints (Tromposch and Kulak, 1987). The code provisions for medium- and high-rise buildings have been based on numerical analyses and engineering judgement.

STEEL PLATE SHEAR WALL RESEARCH PROGRAM

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To verify the guidelines and design principles provided in the latest version of CAN/CSA-S16.1-94, and to broaden the scope of the code, an experimental testing program accompanied by numerical investigation was conducted at the University of British Columbia (UBC). This effort was in collaboration with researchers at the University of Alberta and a team of consulting engineers. The objective of the UBC research program was to investigate the behaviour of steel plate infill panels and boundary frames under simulated earthquake motions and slow quasi-static cyclic loading. Parallel analytical studies were also conducted to aid in the design of specimens and to compare with test results and produce design recommendations. An important part of the experimental program was to monitor the formation of diagonal tension field action combined with diagonal compression buckling and frame action, with the aim of assessing their influence on the overall behaviour of the steel plate shear panels. The stability of the panel hysteresis curves under intense seismic and quasi-static cyclic loading was of primary concern. The effects of the full moment resistant frame along with the presence of steel plate shear panels to minimize the influence of pinching in the hysteresis loops and to ensure satisfactory seismic performance was also studied.

Experimental Investigation

Two single storey and one four-storey single bay steel plate shear walls with unstiffened infill panels and moment-resisting beam-to-column connections were tested under a sequence of low, moderate and severe cyclic loading. The single storey specimens represented the bottom storey panel of the four-storey specimen. The specimens were quarter-scale models of a typical office building core. Column-to-column and beam-to-beam dimensions were 900mm. All material was hot rolled: beams and columns S75x8 sections and plate thickness 1.5mm. The two single-storey specimens differed in that the second had a double top beam to simulate the anchorage from upper storeys. All specimens were loaded cyclically: specimen 1 with single cycles only and the other specimens with triple cycles for each amplitude step. Test results in Figures 3 & 4 show only one-quarter of the load-displacement curves.

The single storey specimens experienced significant inelastic deformations of six times the deflection corresponding to the point of first significant yielding. The specimens proved to be very stiff, compared to the bare frame, showed good ductility and energy dissipation characteristics, and exhibited stable behaviour at very large deformations following many cycles of loading. The results of both tests demonstrated that the infill steel plates significantly reduced demand on the moment-resisting frame by producing redundant diagonal storey braces that alleviated the demand on the beam-to-column connections. For the four-storey specimen, a maximum displacement of one and a half times the corresponding yield displacement recorded in the previous cycle was achieved prior to a global instability failure, propagated by yielding of the columns. The specimen proved to be somewhat more flexible than the one-storey specimens. This was expected because the influence of overturning moment is more significant as the height of a structure increases. Full details of the cyclic tests for all specimens can be found in dissertations by Lubell (1997) and Rezai (1999).

The dynamically tested four-storey specimen was subjected to a number of site-recorded and synthetically generated ground motions with varying intensities. Even though each test gave important information about the dynamic behaviour of the scaled steel plate shear wall specimen, the limited capacity of the shake table prevented the attainment of significant inelastic response in the specimen. More details of the shake table tests can be found in the dissertation by Rezai (1999).

Numerical Investigation

With quasi-static and shake table test results of single and four-storey steel plate shear wall specimens in hand, the capability of the code procedure to predict linear and non-linear response of unstiffened infill panel frames to cyclic storey forces and earthquake ground motions was evaluated. Especially, it was of interest to study how different modelling of shear resistance of thin infill plates would affect the predicted results. The prime objective was to critically assess the procedure presented in Appendix M of CAN/CSA-S16.1-M94 as the basis for numerical analyses. The shortcomings and inconsistencies of the code numerical model in predicting the overall load-deformation relationship of steel plate shear wall frames were addressed. A simple numerical model that is based on the effective panel width and with strips defined at different directions is proposed.

SIMPLIFIED NUMERICAL MODELS

Results from the scaled steel plate shear wall tests were used to verify numerical models and to gain an understanding of how the various methods of modelling the shear resistance of thin infill plates would affect the predicted results. It is known that as an infill plate buckles, the system continues to resist the load by forming a diagonal tension field. The development of tension field action is analogous to a Pratt Truss in which diagonal members resemble the web plate, the upper and lower chords act as the columns, and the vertical struts act as the storey beams. In modelling a steel plate shear wall frame, infill panels may be similarly modelled as a series of inclined strip members, capable of transmitting tension forces only, and oriented in the same direction as the principal tensile stresses in the panel.

Parallel Strip Model

A simplified strip method in the Canadian Steel Design Code (CAN/CSA-S16.1-M94) is based on the theory of pure diagonal tension by Wagner (1931), which does not account for any shear carried by the thin plates prior to shear buckling. (Generally buckling occurs at low lateral load levels because of large panel width to thickness ratio and because of fabrication induced out-of-plane imperfections). The shear panels are represented as a series of inclined strip members, capable of transmitting tension forces only, and oriented in the same direction as the principal tensile stresses in the panel. Each strip is assigned an area equal to the product of the strip width and the plate thickness. A minimum of 10 strips, each of width equal to the strip spacing, is recommended by the code (Figure 1).

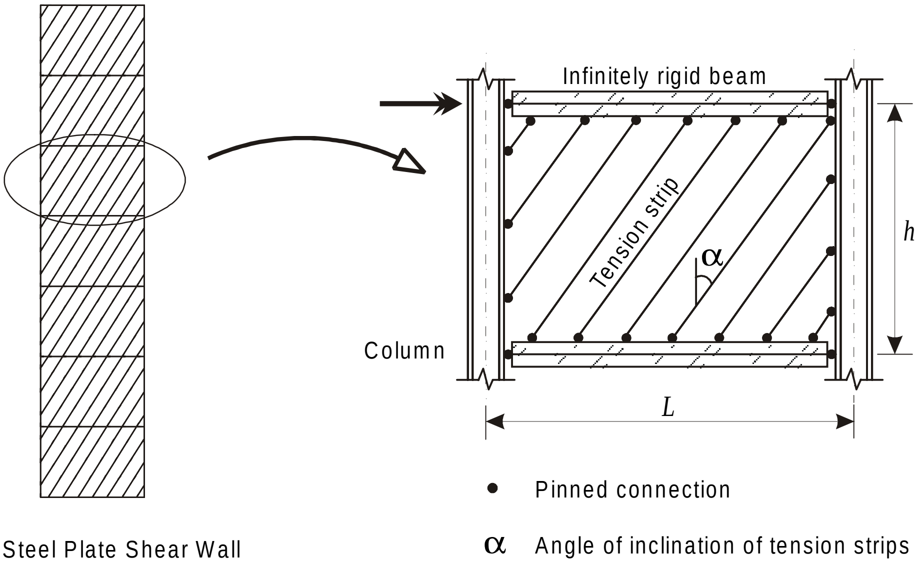

Figure 1:Parallel strip model representation of a typical steel plate shear wall panel

The derivation of the angle of inclination of the tension strips is based on the shear mode deformation of an infill panel, using least work principles, derived by Thorburn et al. (1983) and later modified by Timler and Kulak (1983). The columns are assumed to be continuous while the beam-to-column connections are considered to be pinned. The effects of column bending and axial rigidities are considered in the derivation. The storey beams are assumed to be infinitely rigid in bending, which is due to the assumption that tension field forces for any two adjacent storeys differ very little and oppose one another, therefore the net vertical forces acting on the beam would be negligible.

Proposed Multi-Angle Model

The derivation of the angle of inclination of the tension field is established on the basis that the web plate has no shear resistance prior to buckling and that it behaves elastically. The distribution of the stress field across the panel width is considered to be constant. From tests in this study and also by previous researchers (Driver, 1997) it is known, however, that tension field stresses are non-uniform and that the behaviour of the panels is somewhat more complex than a series of strips at a constant angle can represent. The experimental studies at UBC indicated that the angle of the tension strips was closer to the vertical at the corners than the mid-point of the plate. This was primarily related to the interaction of infill plates and boundary elements at the corners.

In the proposed model the infill plate panels in a multi-storey shear wall frame are also replaced by a series of strip elements. As the corners of an infill steel panel are connected to the relatively stiff beam-to-column joints, they attract a considerable portion of the steel plate membrane forces. The surrounding elements are then responsible for anchoring the remaining portion of the infill plate in-plane forces. Because the degree of magnification and inclination of the infill plate principal tension stresses are different at various locations in the plate, the tension strips are placed at different angles. To simplify the modelling, the tension strips are placed diagonally between opposite corners and from the corners to the mid-span of boundary members, as shown in Figure 2.

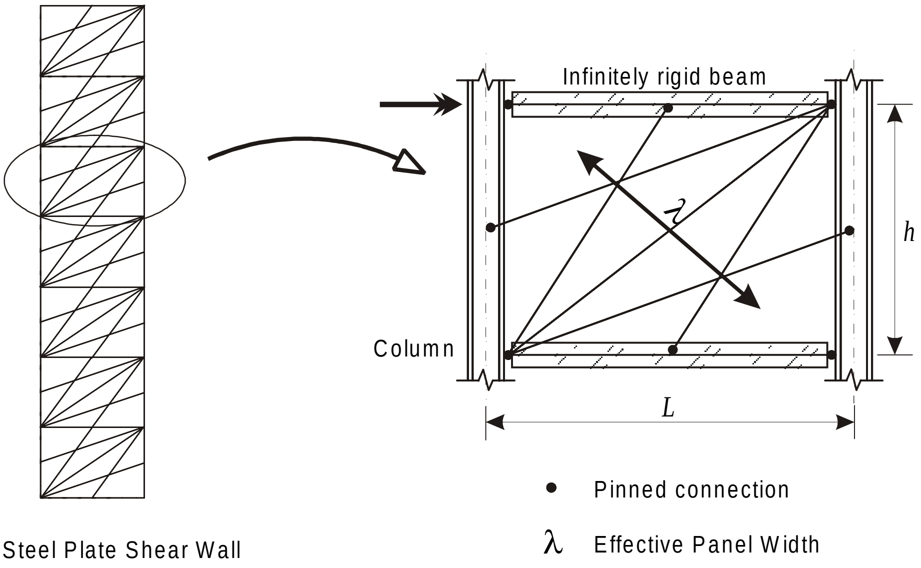

Figure 2: Proposed multi-angle strip model representation of a typical steel plate shear wall panel

The areas of tension strips are assigned based on the degree of interaction between the infill wall and boundary frame. This composite action is greatly dependent on the rigidity of boundary members. The concept of equivalent tension-only truss elements was used to represent the contribution of the infill panels to the stiffness and strength of the infilled frame. In this regard, the effective width of the infill plate (cross-sectional area of the truss element) in resisting storey shear is a key parameter. The principle of least energy concept adopted by Timler and Kulak (1983) which includes the elastic strain energy of a panel, approximated as a series of discrete diagonal tension strips, together with the axial and bending strain energy of the columns, are used. It is noted that the tests at UBC and UofA confirmed the very small contribution of the beam axial energy term in the total work expression. Therefore, the cross-sectional area of storey beams in a multi-storey building is considered as infinity and, therefore, the elastic energy of beam axial force is ignored. The detailed derivation of the effective width of a steel panel in resisting storey shear is presented in the dissertation by Rezai (1999).

Numerical Model Parameters

All modelling was conducted using the non-linear frame analysis program CANNY-E (Canny Consultants, 1996). Experimentally determined material strengths, and published section properties were used as input data for the analytical models. For the present pushover analyses three different load-deformation characteristics were employed. A uniaxial hysteresis model with tri-linear skeleton curve behaviour was selected for the storey beams, while a tension-only bi-linear skeleton curve was chosen to model the infill plate strip members. The columns were modelled using multi-spring elements with tri-linear properties, capable of accounting for the interaction between axial and flexural forces. Column element shear was simulated with a linear model.

ANALYTICAL MODELS AND RESULTS

Single Storey Specimens

Four different strip models were created of the single storey specimens: three with parallel strips at angles 45°, 37° and 55° and one multi-angle strip model. The main reason for creating three different angles of inclination of tension strips was to study the effects of various modelling assumptions on the analytical results. The 37° angle was computed using the Canadian code recommended expression.

The results of the CANNY-E nonlinear analyses of the numerical models for the first single storey specimen are illustrated in Figure 3a. It should be noted that this specimen had a flexible top beam, resulting in a relatively high tension field angle. This is evident as both the 45° and 37° models significantly overpredicted the elastic stiffness and ultimate strength of the specimen. This could be attributed, in part, to the variation in the angle of inclination of principal tension stresses at different locations on the plate and flexibility of the storey beam. The 55° and multi-angle models fared better on both accounts.

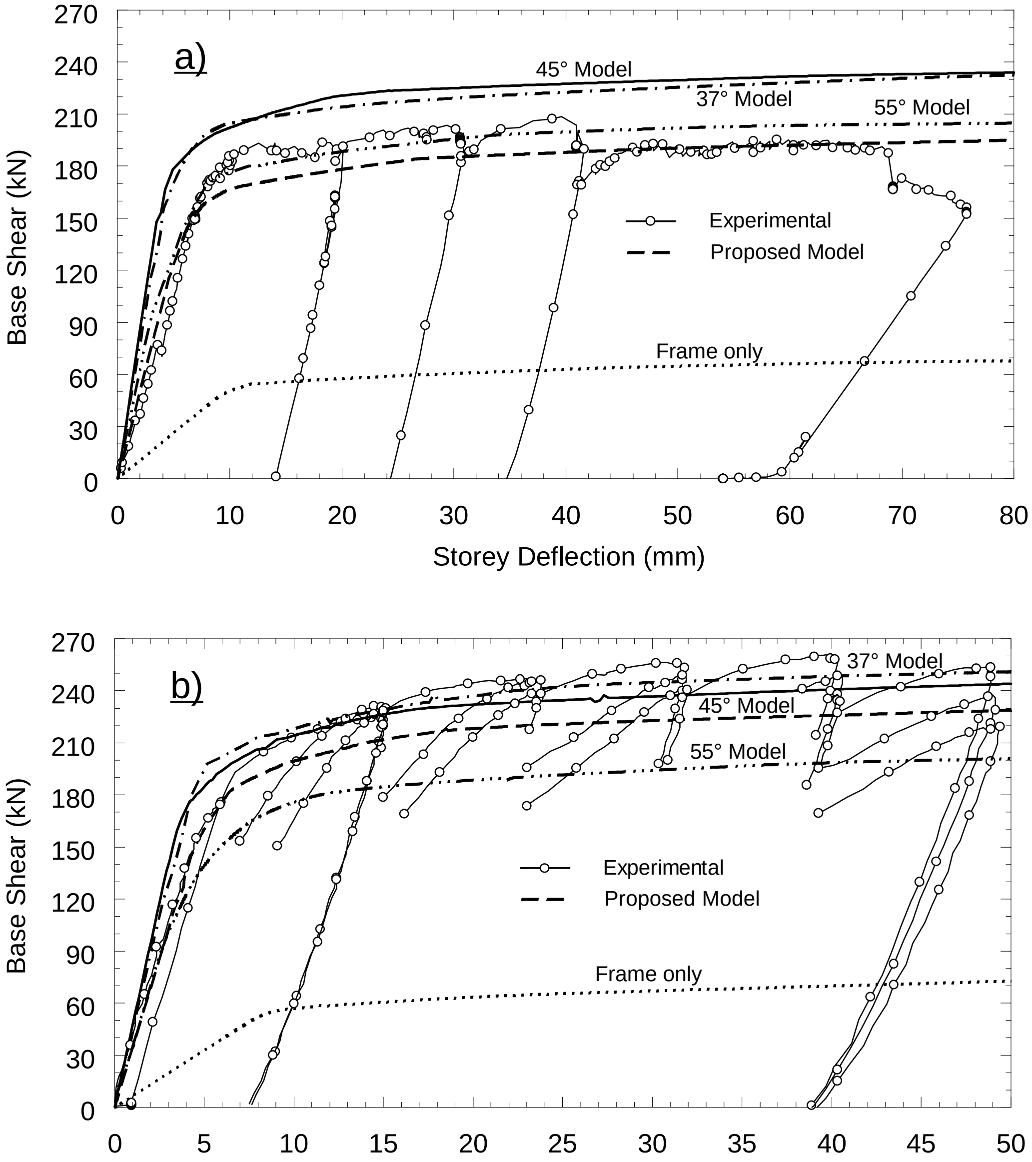

Figure 3: Comparison of push-over load-deflection curves of CANNY-E models with envelope curve of cyclic test results for the a) first and b) second single storey specimens

The results of the CANNY-E nonlinear analyses of the numerical models for the second single storey specimen are illustrated in Figure 3b. This specimen had a very stiff top beam, resulting in a somewhat steeper tension field. This is evident as the 37° and 45° models produced much better results. The proposed multi-angle model gave a good representation of the panel elastic stiffness , but slightly underpredicted the stabilized envelope curve after three displacement cycles. For reference, the load-deflection curve of the bare moment-resisting boundary frame is also shown in Figure 3. The relatively low stiffness of the moment-resisting frame alone demonstrates the significant contribution of the unstiffened infill plate in enhancing the initial stiffness and strength of the specimen.

Four-Storey Specimen

Parallel as well as multi-angle strip models of the UBC four-storey steel plate shear wall specimen were prepared for the CANNY-E program. To demonstrate the effect of varying the angle of inclination of strips on the load-deflection behaviour of the test specimen, four different parallel strip models at different angles, judged to be near the lower and upper bound of a typical range, were created. These angles were 45°, 37°, 55° and 22°. The 22° angle was calculated based on a flexible column assumption (Thorburn et al., 1983) where a partial tension field forms between storey beams only.

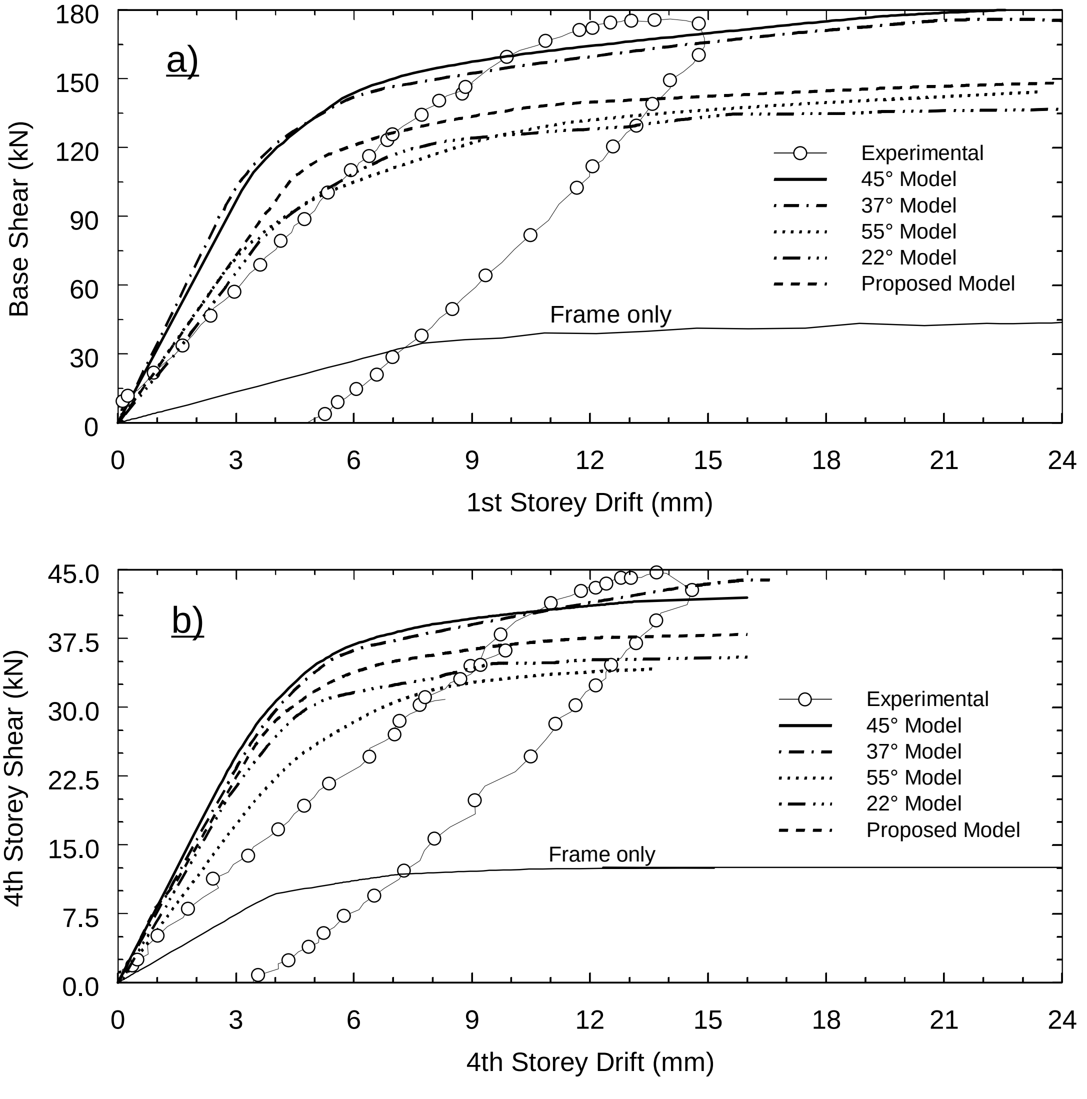

Figure 4: Comparison of push-over load-deflection curves of CANNY-E models with envelope curve of cyclic four-storey test results for the a) first and b) fourth floors

Figure 4 compares results from the different strip models with the experimental load-deformation results for the first and fourth floors. Please note that only one non-linear load cycle was obtained due to a premature column buckling failure. Nonetheless, these results clearly point out some phenomena associated with tall slender shear walls. None of the models gave an accurate representation of the overall load-deflection behaviour of the test specimen. The 45° and 37° strip models predicted elastic deformations that were considerably less than observed experimentally. Interestingly, all three other models reasonably predicted the first storey drift, but significantly overestimated the fourth storey drift of the shear wall. The ultimate strength of the specimen obtained for the first cycle of loading was underpredicted by all analytical models. The best strength values were obtained with models having a shallow strip inclination.

The curve in Figure 4 depicting the behaviour of the moment-resisting frame alone serves to demonstrate the significance of the infill panels' presence in resisting the storey shears and thus increasing the stiffness of the structure. This contribution diminished steadily for the upper floors. This leads to the conclusion that the fourth storey infill plate was only marginally effective in resisting the applied lateral load. This could be attributed to the dominance of a flexural mode caused by the high specimen height-to-width ratio. In a more extensive study by Rezai (1999) much better agreement of numerical and experimental results was achieved for specimens tested by other researchers. These specimens all had lower height-to-width aspect ratios, where the overall behaviour was shear dominated. It should also be pointed out that the UBC specimens had relatively light perimeter frame members compared to the web panel. This might explain the high sensitivity of stiffness and strength of tall shearwalls with respect to modelling parameters.

GENERAL DISCUSSION ON SIMPLIFIED NUMERICAL MODELS

The two important characteristics of the UBC four-storey specimen were the low stiffness and high yield strength values that were not properly captured by the numerical strip models. As mentioned before and confirmed by the experimental evidence, the stiffening effect of infill panels in increasing the overall elastic stiffness of the bare frame is primarily governed by the formation of a diagonal tension field. The extent to which tension field action can be effectively generated in a panel is significantly influenced by the storey height and width of the panel. As confirmed by the experimental investigation of the four-storey specimens at UBC, the boundary moment-resisting frames were significantly less affected by the presence of infill panels at the upper floors compared to the first storey panel that benefited the most. The severity of divergence between computed and actual response may greatly depend on the number of floors and the overall aspect ratio of the frame, as these two parameters are crucial in defining the deformation behaviour of an infilled frame. This could be dominated by overall storey shear or by an overall flexural behaviour (also called chord drift effect). Multi-storey buildings typically exhibit a combination of these two effects. It has been shown that as the ratio of overall height of a multi-storey steel plate shear wall frame to its width increases, the strip model tends to overestimate the elastic stiffness of the structure (Rezai, 1999). To properly model the elastic stiffness characteristic of an infilled frame, an analyst may try to compromise on the strip model (e.g. alter the direction and the layout of the strips) so that good correlation between the experimental and analytical results is obtained. The refined model, however, may very well fail to predict the yield and ultimate strength of the system. This is mainly because the strength and stiffness of a multi-storey steel plate shear wall frame modelled as a series of discrete strip elements at each floor are dependent on each other. This means that as the strips are arranged in a way to reduce the overall stiffness of the frame, the overall strength of the specimen is reduced as well and vice versa. This is the main dilemma for the strip model technique in representing the behaviour of slender multi-storey buildings. The UBC four-storey test specimen exemplified the frustrations of the strip model analogy in predicting its behaviour.

CONCLUSIONS

Results from the reduced scale steel plate shear wall tests were used to verify the accuracy of various numerical models and to gain an understanding on how the various modelling techniques for the shear resistance of thin infill plates would affect the predicted results. In general, the strip models overpredicted the elastic stiffness of the test specimens. The load-deformation behaviour of the specimens was considerably affected by a change of 10° in the angle of inclination of tension strips. The discrepancies between the analytical and experimental results was more dramatic for the four-storey specimen compared to the single storey specimens. This was mainly related to the small overall aspect ratio of the four-storey specimen and, thereby, increased moment to base shear ratio, which resulted in a dominance of flexural deformation (or chord drift) compared to shear behaviour. This effect can be significant for shear walls with relatively light perimeter framing members.

An improved analytical model was proposed for simplified analysis. The proposed model predicted reasonable results for pushover analyses. Even though the proposed model was in closer agreement with the experimental results, compared to the 37° strip model predictions, the elastic stiffness and the yield strength of the four-storey specimen were overpredicted and underpredicted by the proposed model, respectively. This indicates a need for improvements in the modelling to better represent the chord drift effect.

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REFERENCES

Canadian Standard Association, 1994, “CAN/CSA-S16.1-94, Limit States Design of Steel Structures” Sixth Edition, Willowdale, ON.

Canny Consultants Pte. Ltd., 1996, ”Three-Dimensional Nonlinear Dynamic Structural Analysis Computer Program Package, CANNY-E”, October, Singapore.

Driver, R.G., 1997, “Seismic Behaviour of Steel Plate Shear Walls”, Ph.D. Dissertation, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB.

Lubell, A.S., 1997, “Performance of Unstiffened Steel Plate Shear Walls Under Cyclic Quasi-Static Loading”, M.A.Sc. Thesis, Department of Civil Engineering, University of British Columbia, Vancouver, BC, Canada.

Rezai, M., “Seismic Behaviour of Steel Plate Shear walls by Shake table Testing”, Ph.D. Dissertation, University of British Columbia, Vancouver, Canada, 1999.

Thorburn, L.J., Kulak, G.L., and Montgomery, C.J., 1983, “Analysis of Steel Plate Shear Walls”, Structural Engineering Report No. 107, Department of Civil Engineering, University of Alberta, Edmonton, AB.

Timler, P.A. and Kulak, G.L., 1983, “Experimental Study of Steel Plate Shear Walls”, Structural Engineering Report No. 114, Department of Civil Engineering, University of Alberta, Edmonton, AB.

Tromposch, E.W. and Kulak, G.L., 1987, “Cyclic and Static Behaviour of Thin Panel Steel Plate Shear Walls”, Structural Engineering Report No. 145, Department of Civil Engineering, University of Alberta, Edmonton, AB.

Wagner, H. (1931). Flat Sheet Metal Girders with Very Thin Webs, Part I - General Theories and Assumptions. Technical memo No. 604, National Advisory Committee for Aeronautics, Washington, DC.