Report on

## BRACED FRAME SYSTEM FOR TIMBER BUILDINGS

Asif Iqbal

University of Northern British Columbia

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#1200 - 1130 West Pender Street, Vancouver, BC Canada V6E 4A4

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## **BRACED FRAME SYSTEM FOR TIMBER BUILDINGS**

## ABSTRACT

Advanced sustainable lateral load resisting systems that combine ductile and recyclable materials offer a viable solution to resist seismic load effects in environmentally responsible ways. This paper presents the seismic response of a post-tensioned timber-steel hybrid braced frame. This hybrid system combines glulam frame with steel braces to improve lateral stiffness while providing self-centreing capability under seismic loads. The proposed system is first presented. A detailed numerical model of the proposed system is then developed with emphasis on the connections and inelastic response of bracing members. Various types of braced frames including diagonal, cross and chevron configurations are numerically examined to assess the viability of the proposed concept and to confirm the efficiency of the system. A summary of initial findings is presented to demonstrate usefulness of the hybrid system. The results demonstrate that the proposed system increases overall lateral stiffness and ductility while still being able to achieve self-centring. Some additional information on connection details are provided for implementation in practical structures. The braced-frame solution is expected to widen options for lateral load resisting systems for mid-to-high-rise buildings.

#### **INTRODUCTION**

Over the last decade, the "Low-damage" concept has been successfully implemented in wood building subassemblies (e.g. walls, columns and beam-column joints) and basic structural systems such as frames and wall systems. The technology has already been applied in a number of wooden buildings within and outside New Zealand confirming the practical applicability [1-4]. The structural systems in those buildings include individual or coupled shear walls, columns and moment-resisting frames for low-rise buildings. For buildings with greater height it is necessary to improve the lateral stiffness of the seismic force resisting system as the application of momentresisting frames become inefficient. A viable alternative is to use steel braced frames with higher stiffness and strength to meet the increased drift demands. Numerical analysis is used to investigate the response of the proposed system. Additionally, some practical considerations are reviewed.

## **POST-TENSIONED TIMBER BRACED FRAMES**

Timber braced frames have been investigated for seismic applications [5-6] including some special braced frames with combination of timber and steel [7-9]. In post-tensioned frame the arrangement achieves self-centreing due to post-tensioning while the members remain elastic.



Figure 1: Timber braced frame

The post-tensioned timber-steel hybrid braced frame combines Glulam frame with steel braces. The system offers a high lateral stiffness due to the presence of the steel braced frame and improved seismic performance as a result of self-centring capability of the timber structure. The connection between the timber and steel structures is detailed such that a reliable energy dissipating capacity is obtained and a proper seismic load path is provided to achieve the expected response under seismic ground motions.

## JOINTED DUCTILE CONNECTION CONCEPT

In jointed ductile connections for timber conventional post-tensioning is combined with timber structures made of engineered wood products to produce highly efficient systems. The post-tensioning ensures self-centering optionally with ductility provided by additional energy dissipating elements within the connections (Figure 2).



Figure 2: Combination of post-tensioning and energy dissipation producing "Flag-shaped"

hysteresis loop

#### **CONNECTION DETAILS**

In practical arrangements replaceable ductile elements protects the structural members from serious damage through absorbing energy during seismic events (Figure 1). Engineered wood products have been found to be particularly suitable for this type of applications because of their superior strength characteristics compared to rough sawn timber and the concept has been applied to different engineered wood products such as Laminated Veneer Lumber (LVL) and, Glue Laminated Timber (Glulam). One of the common energy dissipating connection consisted of axially loaded buckling-restraint bars, encased in steel tubes. It is expected that large inelastic deformations are achieved when using the 'fuse' with possibility of replacement after yielding.

#### NUMERICAL MODELS

A detailed numerical model of the proposed system is developed in the Open System for Earthquake Engineering Simulation (Opensees) software [10-11]. The model includes a twostorey timber-steel braced frame (TSBF). A fibre-based model is used to simulate the seismic response of the frame. Special attention is paid to the simulation of the connections and inelastic response of bracing members. Material and geometric nonlinearities are considered. The model was validated against previous experimental results on timber and steel frames. This study focuses on a single- and two-storey timber-steel braced frames with cross bracing configuration to evaluate the seismic response of the proposed system.

#### MODEL DEVELOPMENT

In order to simulate the seismic behaviour of the timber steel-braced frame, two simplified models were developed using Opensees: 1) one-storey steel brace frame and 2) timber moment frame. For the steel frame, the results of the numerical analysis were validated against the previous experimental test data obtained from cyclic testing of single-storey steel braced frame [12]. These two models will then be combined together to create a timber steel-braced frame.

The numerical model of steel braced frame is presented in Figure 3. The material of all the steel elements is assigned as Steel02, which is known as Giuffré-Menegotto-Pinto Model with kinematic and isotropic hardening parameters. The material parameters were determined based on the calibration studies performed by Imanpour et al. (2016) [13].

In the numerical model, the ends of the columns and the bracing members are pin connected, which suggests that the bracing members provide frame the lateral resistance through a truss action. The beam is modelled as elastic beam-column element with elastic steel properties, while the columns are simulated by six of force-based beam column fibre elements with discretization of the cross section, which accounts for the geometry and material non-linearity. Each brace half is simulated using five forced-based beam-column fibre elements with discretization of the cross-section. Brace connections are modelled as rigid links at both ends of each brace half as shown in Figure 3. The gusset plates are simulated using zero-length rotational spring elements to allow for in-plane buckling of the braces as suggested by Hsiao et al. (2012). One of the bracing members is continuous (left-bottom to right-top), while other one is separated into two discontinuous segments; as a result, two zero-length rotational springs are assigned in the middle of the discontinuous brace. The frame is constrained against out-of-plane movement at the base and top

ends of the columns. Eventually, the initial imperfections of columns and braces are considered. The former value is 1/1000 of the total length, while the latter one is 1/500.



Figure 3: Steel braced frame model

In order to take the P-delta effects into account, a leaning column with truss elements was added to the model; the building gravity load corresponding to the studied braced frame was applied to the leaning column. Note that the leaning column is not presented in the Figure 3.

Figure 4 shows the cyclic behaviour of steel braced frame of Figure 3 where the braces buckle and yield under the lateral load. As shown, the numerical model can properly simulate the tension and compression behaviour of the steel braces Brace axial force-axial displacement response obtained from a single storey braced frame is shown in Figure 5. It is obvious that the buckling behaviour have been simulated.



Figure 4: Lateral force-displacement response of the single-storey steel braced frame.



Figure 5: Axial force-axial displacement of the brace.

The numerical model of the post-tensioned (PT) timber beam-column connection was also developed in Opensees to understand the behaviour of the timber frame. The numerical model of the timber frame is shown in Figure 6. The column is pin connected to the ground and the end of beam is fixed connected using a roller. The reversed cyclic lateral displacement demand is applied at the top end of the column. The behaviour of timber connection with post tensioning in the beam can be simulated using a series of the zero-length rotational spring and elastic beam column elements. The post-tensioning behaviour is represented as a bi-linear elastic material, and the stiffnesses of the post-tensioning rotational springs were calibrated with the experimental test results in [14]. The model developed can appropriately capture the post tensioning response as well as the rocking mechanism implemented in the connection as suggested by previous research studies [14]. Meanwhile, it is also important to include the flexibility of joint panel into account using an elastic zero-length rotational spring at the beam-column connection. The stiffness of elastic rotational spring is 30 kN-m suggested by the value in [14]. The remaining members are simulated using elastic beam column elements in the Opensees model.



Figure 6: PT timber beam-to-column connection model.

## MODEL VALIDATION

The proposed models were compared with two available experimental test data. Overall, the simulation results can successfully match with the test data, which suggests that the numerical models can predict the frame responses with an acceptable accuracy.

The experiment chosen to validate the proposed model is the specimen X6-C, X-braced frame, in the [12]. The material properties, member sections, frame dimensions and the loading protocol can be found in [12]. As shown in Figure 7, the model of steel braced frame in Opensees is capable of reproducing the cyclic behaviour of the tested frame, verifying the accuracy of the steel braced frame model.



Figure 7: Validation of the steel braced frame model (Archambault 1995).

The PT timber beam-to-column connection was tested under reversed cyclic displacement protocol given in [14]. Each specimen tested has a different value of post-tensioning force in the tendon including 50, 100, 150, 200 and 250 kN. The one end of post-tensioned tendon is anchored in the column, while another end is anchored at the beam section. The displacement is applied at the top end of the column to evaluate the post-tensioning response of the connection.

Figure 8 shows the comparison between the numerical simulations and the test results for various post-tensioning forces. Since the specimens and the numerical model does not have any energy dissipation device, the simulation results present as perfect self-centring or perfect bi-linear behaviour. The comparison between numerical results and test data demonstrates that the proposed model for PT timber frame can predict the inelastic self-centring response appropriately.



Figure 8: Validation of the PT timber beam-column connection (Smith, 2014)

The results obtained from two validation study presented, the cyclic behaviour of steel brace and timber connection can be properly simulated using the proposed models. The proposed hybrid frame model including the timber frame and steel brace is therefore created using the timber columns and beam with elastic beam column elements, the flexible panel zone with elastic rotational spring, and the rotational spring with bi-linear stiffness.

#### **ANALYSIS RESULTS**

After verifying both steel brace and timber frame models, the one-storey timber- steel braced frame was developed and analyzed under the cyclic displacement loading history. The timber-steel braced frame model in Opensees is presented in Figure 9. The story height is 3658 mm with 4877 mm spacing. The columns and beams are made of Glulam 32h, while the steel yield stress is 345 MPa. The detailed dimensions of the single-story TSBF are listed in Table 1.

Floor Frame Column Beam **Brace Section** Height span Section Section Rectangular Rectangular 4877 W64 x 64 x 4.8 3658 306 x 306 200 x 300

**Table 1:** Geometry of the single-story TSBF (Unit: mm)

The overall response of the hybrid TSBF is presented in Figure 11. The frame deformed-shape and the buckling of the brace at 1.0% storey drift is presented in Figure 10. The cyclic response of the single story TSBF frame is presented in Figure 11, which is a typical behaviour of X-braced frame with pinching response. The reason of pinching response is from the hardening of the steel. The stiffness degradation of the frame and the energy dissipation of the TSBF are detected due to the buckling of the braces and the yielding of the steel, respectively. The residual displacement of the TSBF is also shown due to the buckling and yielding of the steel braces.



Figure 9: Single-storey TSBF model in Opensees.



Figure 10: Deformed shape of the single-storey TSBF at 1.0% storey drift.



Figure 11: Single-story timber frame with steel braces

To examine the seismic behaviour of two-storey TSBF, two types of the TSBF were then created: 1) the section of braces in both stories are the same. 2) the section of braces in 2<sup>nd</sup> story is smaller. Each story height is 3658 mm with 4877 mm spacing. The columns and beams are made of Glulam 32h, while the steel yield stress is 345 MPa. The dimension of columns and beam in 2<sup>nd</sup> story are the same as in the 1<sup>st</sup> story. The detailed dimensions of two types of the two-story TSBF are listed in the Table 2.

Туре	Floor Height	Frame span	Column Section	Beam Section	Brace Section
1	3658	4877	Rectangular 306 x 306	Rectangular 200 x 300	W64 x 64 x 4.8
2	3658	4877	Rectangular 306 x 306	Rectangular 200 x 300	W57 x 6 x 4.8

Table 2: Geometry of two types of the two story TSBF (Unit: mm)

The numerical model of type 1 developed in Opensees is shown in Figure 12. And the deformed shape is shown in Figure 13. The buckling behaviour of the braces only occurred in the 1<sup>st</sup> story, while the braces in 2<sup>nd</sup> story remained elastic. The reason is that the columns are pin connected to the ground, which will have single curvature deformation. And the deformed shape of their upper parts (2<sup>nd</sup> story) remain relatively straight than the bottom parts (1<sup>st</sup> story); as a result, the braces in 2<sup>nd</sup> story did not receive significant axial deformation.



Figure 12: Two story TSBF model in Opensees



Figure 13: Deformed shape of type 1 two-story TSBF at 1% storey drift.

The cyclic simulation result of type 1 TSBF is shown in the Figure 14. where the lateral forcelateral displacement of each story is presented. The global response is similar to the single story TSBF, since both model presented braces buckling in the 1<sup>st</sup> story. But the stiffness of unloading parts is smaller than its counterpart in single story TSBF, which indicates that the two story TSBF is softer than single story TSBF due to more gravity load and higher story. The stiffness degradation of the frame and the energy dissipation of the TSBF are detected due to the buckling of the braces and the yielding of the steel, respectively. The residual displacement of the TSBF is also shown due to the buckling and yielding of the steel braces.



Figure 14: Cyclic behaviour of type 1 of 2-story TSBF

The axial reaction of 1<sup>st</sup> story braces and 2<sup>nd</sup> story braces are shown in Figure 15 and Figure 16. In the former one, the buckling behaviour is significant, and demonstrated a dramatic difference in compression and tension, which is a typical buckling reaction; while for the latter, the brace member remains elastic and linear, and did not present any buckling behavior, since the axial displacement is small, only 5 mm at the end of the simulation.



Figure 15: Axial behaviour of the brace in 1<sup>st</sup> story



Figure 16: Axial behaviour of the brace in 2<sup>nd</sup> story

The deformed shape of model type 2 is shown in Figure 17. By reducing the dimension of the  $2^{nd}$  story braces, the inelastic behavior of the braces only occurred in the  $2^{nd}$  story, while the braces in  $1^{st}$  story remained elastic. The reason is that the buckling resistance of braces in  $2^{nd}$  are less than the braces in  $1^{st}$  story, and the axial force of the braces in  $2^{nd}$  story is not significant enough to trigger the buckling behavior of braces in  $1^{st}$  story.

The simulation results are shown in Figure 18, Figure 19 and Figure 20. The global response in Figure 18, presents less energy dissipation area, less lateral resistance and less residual displacement. The reason can be found in the following two graphs. In the Figure 19, the 1<sup>st</sup> story brace remain elastic and the axial deformation is under 6 mm, which is not enough to cause brace buckling. In the Figure 20, the buckling force of the brace is close to zero and the braces did not yield at that stage causing less residual deformation, and the tension force is below the value of 300 kN, which is lower than the buckling force in type 1 model; hence, the buckling response of 1<sup>st</sup> story could not be triggered. Furthermore, since the axial force of the braces decreased, the lateral resistance dropped down.



Figure 17: Deformed shape of type 2 two-story TSBF at 1% storey drift.



Figure 18: Cyclic behaviour of type 2 of 2-story TSBF



Figure 19: The brace in 1<sup>st</sup> story remained elastic



Figure 20: The buckling behaviour of brace in 2<sup>nd</sup> story

#### **BRACED FRAME CONNECTION RESPONSE**

Beam-Column Connections with representative details were prepared and tested to investigate response of braced frames. The beam and column were timber members with post-tensioned connection. Two types of steel braces were used: flat bars and round bars. Figures 21 and 22, respectively, show the details of the test specimens. The cyclic responses of the two types are presented in Figures 23 and 24 respectively. The displacements of the specimen with flat bar are greater than those of the round bar specimen as expected; otherwise responses at the two levels are very similar. The change in stiffness happens when there is gap opening at the beam-column joint interface. The elasto-plastic response results in significant energy dissipation, as visible in the hysteresis loops, can also leave small residual displacements. The self-centering and hysteretic energy dissipation capacities are evident.



Figure 21: Post-tensioned timber frame connection with steel flat bar brace



Figure 22: Post-tensioned timber frame connection with steel round bar brace



Figure 23: Response of frame connection with flat bar brace



Figure 24: Response of frame connection with round bar brace

Connections including the post-tensioned timber frame and steel braces is modelled using the timber columns and beam with elastic beam column elements, the flexible panel zone with elastic rotational spring, the rotational spring with elastic bi-linear stiffness simulating the post-tensioned behavior and braces members with inelastic Steel02 material in Opensees [10]. Cyclic responses of the frame connection with similar arrangements in are presented in Figures 25 and 26 respectively. The deflections are understandably higher for the more flexible frame with round bar braces. For the same reason the bilinear elastic nature of response is less prominent in the frame with flat bar braces, as there is smaller gap opening and change in stiffness at beam-column joints.



Figure 25: Numerical model result of frame connection with flat bar brace



Figure 26: Numerical model result of frame connection with round bar brace

## **RESPONSE OF BUILDINNG FRAMES**

The cyclic responses of a five-story frame at the 1<sup>st</sup> and 5<sup>th</sup> story levels are presented in Figures 27 and 28 respectively. The displacements at the 5<sup>th</sup> story are greater than those at the first story as expected; otherwise responses at the two levels are very similar. The post-tensioned-only frame has bi-linear elastic response with no residual displacement. The change in stiffness happens when there is gap opening at the beam-column joint interface. The braced frame without post-tensioning initially behaves elastically and then response become elasto-plastic as the braces yield in tension. It is noticeable that the braced frame has significantly higher initial stiffness compared to the posttensioned-only frame, suggesting higher lateral load resistance. The elasto-plastic response results in significant energy dissipation, as visible in the hysteresis loops, can also leave small residual displacements. Response of the frame with both post-tensioning and braces is essentially summation of the responses of the frame with them separately. The lateral forces are higher compared to the braced frame as a result of additional resistance due to post-tensioning. At the same time, the self-centering and hysteretic energy dissipation capacities of the post-tensionedonly and the braced-frame, respectively, are retained.



Figure 27: Response at 1st story of 5-storied frame



Figure 28: Response at 5th story of 5-storied frame

The cyclic responses of the 1<sup>st</sup> and 10<sup>th</sup> story of a ten-story frame with similar arrangements in are presented in Figure and Figure respectively. The plots are similar to those for the 5-storied frame. The deflections are understandably higher for the more flexible structure. For the same reason the bilinear elastic nature of response of the post-tensioned-only frame is less prominent, as there is smaller gap opening and change in stiffness at beam-column joints. As for the 5-storied model, the braced frames here with and without post-tensioning exhibit significant energy dissipation and self-centering ability.



Figure 29: Response of 1st story of 10-storied frame



Figure 30: Response of 10th story of 10-storied frame

#### CONCLUSIONS

As more and more all timber structures are planned for high-seismic regions and there is expectation from the societies to design structures that meet higher than life safety performance objectives. The post-tensioned hybrid braced-frame solution is a novel idea that has the potential to be considered as a practical alternative for lateral load resistance systems in mid-to-high rise timber structures. Results from numerical models demonstrated that the concept promises to offer better performance by taller timber structures under lateral loads. That is particularly true for seismic applications with significant energy dissipation and almost complete re-centering ability. Comparisons against traditional braced frames also confirm utility of adding post-tensioning to the system. Some additional aspects such as connection arrangements need to be investigated before the new system can be applied in a practical structure.

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#### REFERENCES

- [1] Palermo A., Pampanin, S., Fragiacomo, M., Buchanan, A. H. and Deam, B. L. Innovative Seismic Solutions for Multi-storey LVL Timber Buildings. In: 9th World Conference on Timber Engineering, CD-ROM, 2006.
- [2] Newcombe, M., Pampanin, S., Buchanan, A. and Palermo, A. 2008a. Section Analysis and Cyclic Behaviour of Post-Tensioned Jointed Ductile Connections for Multi-Story Timber Buildings. Journal of Earthquake Engineering, 12 (Supp 1): 83-110.
- [3] Newcombe, M., Pampanin, S., Buchanan, A. and Palermo, A. 2008b. Seismic Design and Numerical Validation of Post-tensioned Timber Frames, Proc. of 14th World Conference on Earthquake Engineering, Beijing, China, 8 p. paper in CD-ROM proceedings.
- [4] Expan Ltd. 2013. Post-tensioned Timber Buildings Design Guide, Part 1-3, Christchurch, New Zealand.
- [5] POPOVSKI, Marjan, PRION, Helmut G. L., KARACABEYLI, Erol, "Shake Table Tests on Single-Storey Braced Timber Frames", *Canadian Journal of Civil Engineering*, Vol. 30, December 2003, pp. 1089-1100.
- [6] POPOVSKI, Marjan, KARACABEYLI, Erol, "Force Modification Factors and Capacity Design Procedures for Braced Timber Frames", The 14th World Conference on Earthquake Engineering, October 2008.
- [7] Gilbert, C., Gholich, R., Erochko, J. Nonlinear dynamic analysis of innovative hybrid timbersteel buildings. The 11th Canadian Conference of Earthquake Engineering, 2015, Victoria.

- [8] Gilbert, C., Erochko, J. ADAPTATION OF ADVANCED HIGH R-FACTOR BRACING SYSTEMS INTO HEAVY TIMBER FRAMES. The 11th Canadian Conference of Earthquake Engineering, 2015, Victoria.
- [9] Blomgren, H., Heavy Timber Buckling-Restrained Braced Frames, Mass Timber Research Workshop, Forest Products Laboratory, Madison, 2015.
- [10] Opensees 2014 Open System for Earthquake Engineering Simulation, opensees.berkeley.edu/.
- [11] McKenna, F., Fenves, G. L., Scott, M. H., & Jeremic, B. Open System for Earthquake Engineering Simulation (Opensees) [Computer Software]. University of California, Berkeley, Pacific Earthquake Engineering Research Center, 2000.
- [12] Archambault, M. H., Filiatrault, A., & Tremblay, R. (1995). Étude du comportement séismique des contreventements ductiles en X avec profiles tubulaires en acier. Département de génie civil, Section structures, École polytechnique de Montréal.
- [13] Imanpour, A., Tremblay, R., Davaran, A., Stoakes, C., & Fahnestock, L. A. (2016). Seismic Performance Assessment of Multitiered Steel Concentrically Braced Frames Designed in Accordance with the 2010 AISC Seismic Provisions. *Journal of Structural Engineering*, 142(12), 04016135.
- [14] Smith, T., Ponzo, F. C., Di Cesare, A., Pampanin, S., Carradine, D., Buchanan, A. H., & Nigro, D. (2014). Post-tensioned glulam beam-column joints with advanced damping systems: testing and numerical analysis. *Journal of Earthquake Engineering*, 18(1), 147-167.