A Collaborative Research Program on Performance-Based Design of Innovative Structural Systems for Earthquake Resistance: An Overview

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SUMMARY:
A comprehensive international collaborative research program is being carried out to develop performance-based design methodologies for new and innovative structural systems to provide enhanced performance, safety and economy when subjected to severe load conditions. The research project is a collaborative effort involving a number of researchers and academic institutions in US, Canada, Thailand, Taiwan, Switzerland, and India. The program encompasses experimental and analytical studies focusing on the applications of a design methodology called Performance-Based Plastic Design (PBPD). The PBPD method is a complete design approach that considers factors such as determination of appropriate design lateral forces, member strength hierarchy, selection of desirable yield mechanism, and target drift right from the beginning of the design process.

The focus in the first phase of this program is on developing innovative steel truss girder moment frames with Buckling Restrained Knee Braces for lateral load resistance and energy dissipation under severe seismic loading. This framing system is termed as Buckling-Restrained Knee Braced Truss Moment Frame (BRKB-TMF). The research work involves a comprehensive analytical and experimental investigation of the BRKB-TMF system under monotonic loading and simulated ground motions. The aim of the analytical studies is: 1) to develop behavioral and performance-based models and the PBPD methodology for design of the system, and 2) to evaluate overall behavior of the system under various load scenarios. The experimental studies focus on: 1) study of member behavior, 2) evaluation of connection and subassembly behavior and 3) behavior of full-scale frames under cyclic displacements and representative ground motions.

This paper presents an overview of the research program. The PBPD method is first reviewed. The applications of the PBPD method in design of structures are then presented. Selected key results from various tasks, including development of the BRKB-TMF system and performance assessment are briefly presented. Finally, future planned work including experimental program and related analytical studies are presented.

Keywords: Truss Moment Frames, Innovative Structural Systems, Performance-Based Plastic Design, Collaborative Research

1. INTRODUCTION

Current structural design practice around the world is generally based on elastic structural behavior and accounts for the inelastic behavior in a somewhat implicit and indirect manner. When struck by severe loads such as earthquake, blast, impact, etc., the structures designed by such procedures have been found to undergo large inelastic deformations in a somewhat “uncontrolled” manner. The inelastic activity, which may include severe yielding and buckling of structural members, can be unevenly distributed in the structure. This may result in rather undesirable and unpredictable response, sometimes leading to collapse, or costly repair work.

While the above design practice has served the profession rather well in the past, sustainability concerns and societal demands are pushing the practice to achieve higher levels of performance, safety, and economy over the life time of a structure leading to more sustainable structures, infrastructures, and communities. Thus, codes are moving towards adopting performance-based design framework.

In order to achieve more predictable structural performance under strong earthquake ground motions, knowledge of the ultimate structural behavior, such as nonlinear relations between force and deformation, and yield mechanism of the structure are essential. Consequently, design factors such as determination of appropriate design lateral forces and member strength hierarchy, selection of desirable yield mechanism, and structure strength and drift etc., for given hazard levels should become part of the design process right from the beginning.

One such complete design methodology, which accounts for structural inelastic behavior directly and practically eliminating the need for any assessment or iteration after initial design, has been developed (Goel and Chao 2008). The method is called Performance-Based Plastic Design (PBPD) method. The method has been successfully applied to and validated for common framing systems such as, moment frames, concentric and eccentric frames, and more recently for RC moment frames.

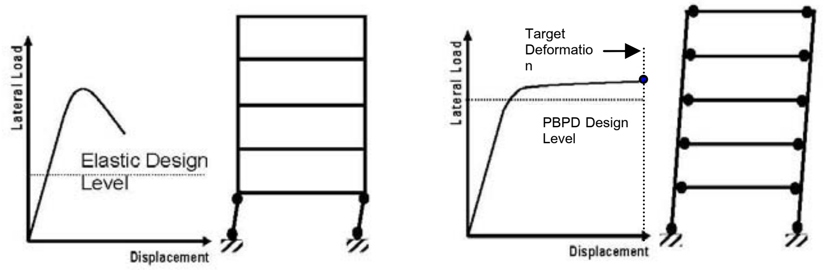
A comprehensive international collaborative research program is being carried out to apply this design methodology to new and innovative structural systems to provide enhanced performance, safety and economy when subjected to severe load conditions. The research project is a collaborative effort involving a number of researchers and academic institutions in US, Canada, Thailand, Taiwan, Switzerland and India. The focus in the first phase of this research program is on developing innovative steel truss girder moment frames with Buckling-Restrained Knee Braces for lateral load resistance and energy dissipation under severe seismic loading. This framing system is termed as Buckling-Restrained Knee Braced Truss Moment Frame (BRKB-TMF). The research work involves a comprehensive analytical and experimental investigation of the BRKB-TMF.

This paper presents an overview of the research program. The PBPD method is first reviewed. The applications of the PBPD method in design and evaluation of structures are then presented. Selected key results are briefly presented. Finally, future planned work including experimental program and related analytical studies are presented.

2. PERFORMANCE-BASED PLASTIC DESIGN

The PBPD method uses pre-selected target drift and yield mechanism as key performance limit states. These two limit states are directly related to the degree and distribution of structural damage, respectively. The design base shear or the required strength of the system for a specified hazard level is calculated by equating the work needed to push the structure monotonically up to the target drift to the energy required by an equivalent EP-SDOF to achieve the same state. Plastic design is then performed to determine the capacity of the designated yielding members (DYMs). The rest of the members are designed to remain elastic.

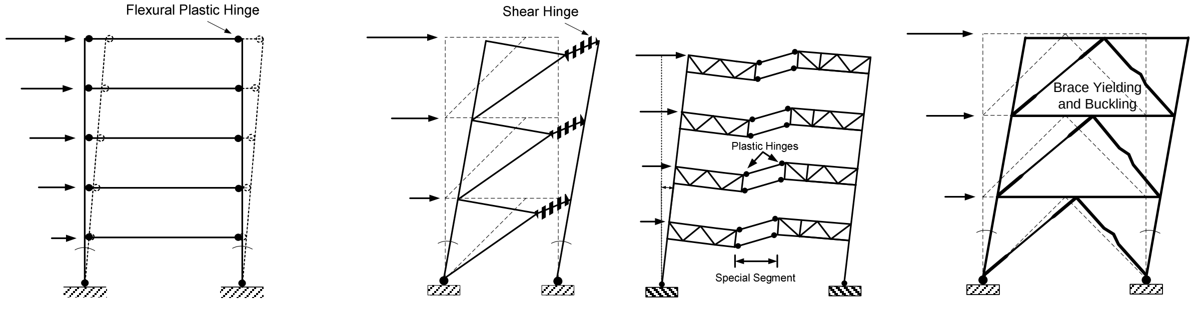
The PBPD method places emphasis on designing structures such that they will behave in a known and predictable manner under extreme events, which essentially means formation of preselected yield mechanism with adequate ductility and strength. The importance of the mechanism-led design process such as PBPD method can be illustrated using the response of a structure subjected to a severe earthquake ground motion. Figure 1 shows possible response of an example structure. A conventional, elastically designed, structure may possess considerable reserve strength beyond the design level. However, the yield mechanism of that structure at ultimate strength level is not known with adequate certainty: an undesirable yield mechanism, such as a story type mechanism shown in Figure 1(a), may develop. In such case, the inelastic activity and energy dissipation are concentrated in only a few elements. The localized rotational demands at the plastic hinges in this case can be very large and may quickly exhaust the ductility capacity of the members leading to collapse of the frame.



(a) Elastic Design Frame (b) PBPD Frame

Figure 1. Response of PBPD Frame

The same structure can be designed using the PBPD method such that a more favorable sway mechanism is achieved. This is illustrated in Figure 1(b). For this mechanism, DYMs consist mainly of the beams whereas the columns remain essentially elastic. The frame reaches the ultimate strength corresponding to the PBPD design base shear level. In this case, for small seismic events where the response remains largely in the elastic rage, the response would be comparable to that of a structure designed by an elastic method. On the other hand, in the extreme events, the energy dissipation and inelastic deformation demands are more evenly distributed along the height of the frame because the structure is designed using the pre-selected yield mechanism. The plastic deformation demands at key locations are limited by selecting an appropriate value of target drift corresponding to the specified hazard level. The PBPD concept can be applied to almost all structural systems (Figure 2).



(a) Moment Frame (b) Eccentrically Braced Frame (c) Special Truss Moment Frame (d) Concentrically Braced Frame

Figure 2. Desirable Yield Mechanism for Different Structural Systems

The base shear or the required strength of the system to limit the deformation of the frame to a specified target drift under a chosen hazard level is calculated by the energy balance concept (Lee and Goel 2001). This concept is based on a key assumption that the energy computed from the monotonic load-deformation response of the inelastic system and the one computed from the corresponding elastic system are related as follows (Figure 3):

$$\gamma E = \gamma \frac{1}{2} M S_v^2 = E_e + E_p \tag{1}$$

where E_e and E_p are, respectively, the elastic and plastic components of the energy needed to push the structure up to the target drift, S_v is the design pseudo-spectral velocity, M is the total seismic mass of the system, and γ is an energy factor (Lee and Goel 2001). The energy factor γ is defined as the ratio of the energy absorbed by the inelastic system to that of the equivalent elastic system and is given by:

$$\gamma = \frac{2\mu - 1}{R_y^2} \tag{2}$$

where μ is the ductility ratio and R_y is the yield force reduction factor. The energy factor can be computed for a given ductility level using suitable R_y-μ-T relationship such as the one suggested by Newmark and Hall (1982). Thus, for seismic design purposes, a target ductility level can be selected and the energy factor can be computed.

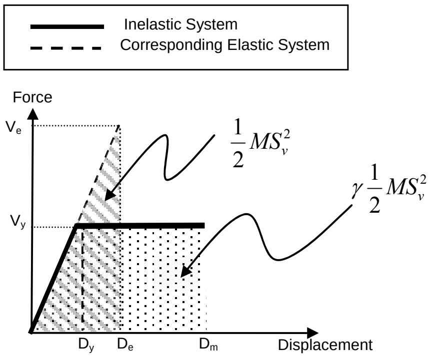


Figure 3. Energy balance concept (Lee and Goel, 2001).

By assuming an appropriate lateral force distribution along the height of the frame and using the selected mechanism, the E_e and E_p components in Equation 1 can be evaluated. Equation 1 can then be solved to obtain the required base shear strength (V_y) of the system (Lee and Goel 2001).

$$\frac{V_y}{W} = \frac{-\alpha + \sqrt{\alpha^2 + 4\gamma C_e^2}}{2} \tag{3}$$

where W is seismic weight of the structure, C_e is normalized design pseudo acceleration (S_a/g) and α is a parameter given by:

$$\alpha = \left(\sum_{j=1}^{n} \lambda_i h_i \right) \frac{\theta_p 8\pi^2}{T^2 g} \tag{4}$$

where θ_p is the target plastic story drift ratio, T is the period, and h_i is the height from the ground to floor level i, and λ_i is the lateral force distribution factor. The advantages of mechanism-based design approach as outlined above include:

1. Enhanced performance and safety, especially under severe ground motions.
2. Ease and economy of repairs after an event, because the structural damage (yielding) is

confined to known members (Designated Yielding Members DYM) and locations. This translates into lower overall life-cycle cost of the structures.

3. The other members not designed to yield, i.e., non-Designated Yielding Members (non-DYM) do not need to be detailed following the stringent ductility requirements as the DYM.
4. Even more importantly, new and innovative structural schemes can be developed by using a variety of ductile energy dissipating members and devices as DYM and moderately ductile members and connections for non-DYM, made of a suitable combination of materials.

It is this last item in the above list of advantages, which is the main focus of the research program described herein. In the first phase, focus will be on innovative framing systems using truss girder moment frames.

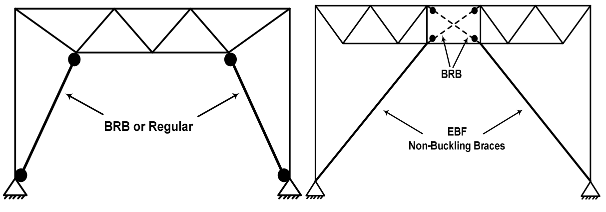
3. PROPOSED STRUCTURAL SYSTEM: BUCKLING-RESTRAINED KNEE BRACE TRUSS MOMENT FRAMES

Open-web steel truss girder frames are very economical and are commonly used for building structures, especially industrial and low-rise ones. Their advantages include 1) light weight, especially for large spans; 2) simple connections to columns; and 3) electrical and mechanical ductwork and pipes can be placed through open webs, without cutting into the clear story heights. However, under extreme load events or accidental overloading conventional truss girders lack proper ductility which often causes sudden and catastrophic failures (Goel and Itani 1994a, 1994b). This shortcoming can be overcome by using energy dissipating elements and design methods such as PBPD. This can lead to new innovative framing systems with enhanced performance in terms of safety and economy. Some possible systems are shown in Figure 4.

These framing systems are very innovative and could easily be considered as belonging to the future generation of high performing structural systems as part of sustainable infrastructure. They have not been conceived nor studied before, but they hold tremendous promise. Detailed study of these high performing sustainable steel truss framing systems requires a comprehensive, broad-based, multi-institutional collaborative research. This research is being undertaken in a series of phases. In the first phase, described herein, a thorough research and development of the system shown in Figure 4(a), termed as Buckling-Restrained Knee Braced Truss Moment Frame (BRKB-TMF) is being carried out currently. Some results are described briefly in the following sections. It is anticipated that other configurations intended for new structures as well as for retrofit of existing structures will be investigated in future research phases.

(a) BRKB-TMF (b) Concentric

Configuration



(c) Eccentric Configuration

Figure 4. Innovative Framing Systems using Truss Girders

4. ANALYTICAL STUDY

The purpose of the analytical study is to verify the performance of the proposed structural system under the design and collapse-level ground motions. The study encompasses development of the performance-based design approach for the structural system and application of state-of-the-art nonlinear dynamic analysis and collapse assessment to evaluate the performance and collapse margin of the system. In addition, life-time performance assessment will be carried out. This result will provide information regarding sustainability in terms of reparability and replacement costs over the life time of the structure.

4.1. Development and Design of Archetype Models

An archetype structure is a model that broadly represents a typical application and characteristics of the proposed structural system. The archetype structure selected for the first phase of this research program is shown in Figures 5. The floor plan consists of 4 bays in the N-S direction and 6 bays in the E-W direction. The structure is assumed to be located in a high seismicity region. An example of the elevation view of a 4-story frame is shown in Figure 6.

In this study, the structure will be designed using the Performance-Based Plastic Design method (Goel and Chao 2008). The design and detailing will follow AISC Specifications (2010). The design work will focus on the main structural members including columns, truss members, and BRB members. The truss-to-column connections, column splices, BRB casing, and BRB-to-truss connections will not be explicitly designed in detail. They are assumed to have adequate strength and ductility.

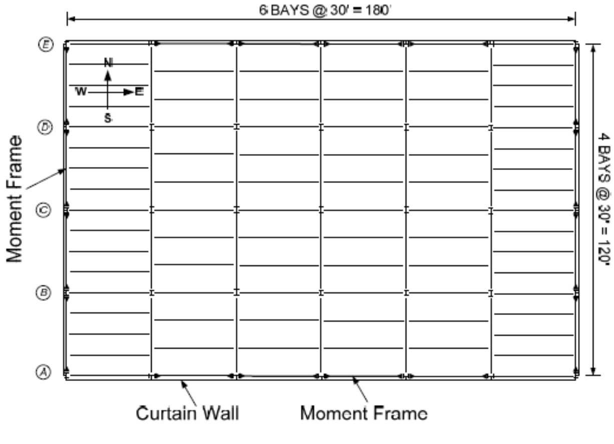


Figure 5. Plan view of Study Building

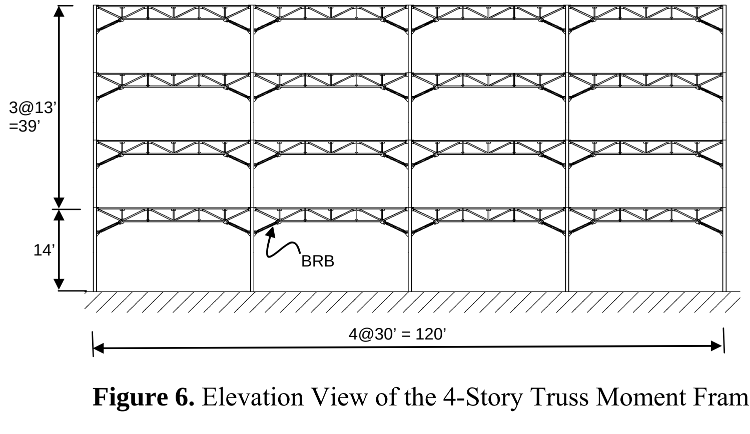
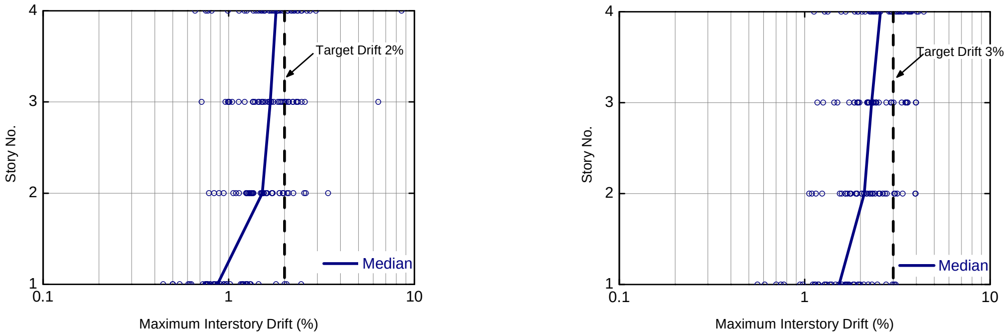


Figure 6. Elevation View of the 4-Story Truss Moment Frame

4.2 Performance Evaluation

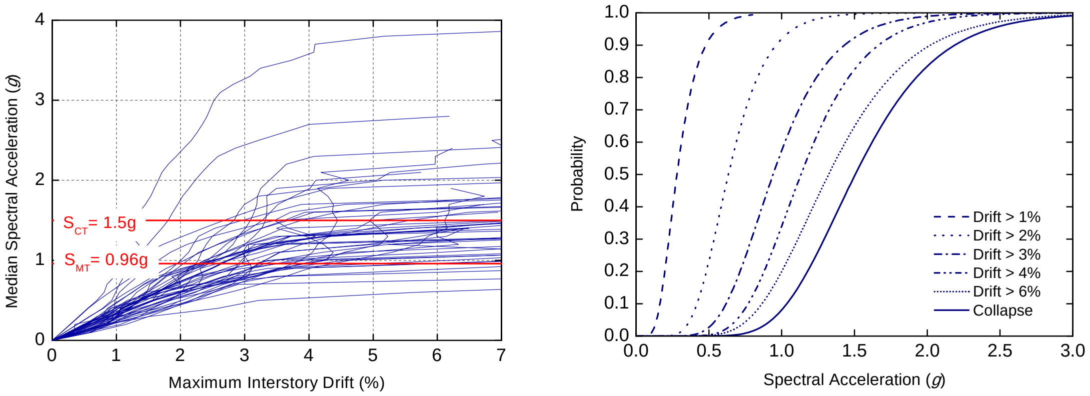
To-date, performance assessment based on the 4-story study frame has been carried out by using inelastic static (pushover) analysis and incremental dynamic analysis (IDA). The pushover analysis was done to determine the overall response, the sequence of inelastic activity leading to collapse, and the failure mechanism. The IDA approach was used to examine the behavior of the structure at different levels of ground motion intensity all the way up to the collapse level. The IDA procedure is a relatively new analytical tool utilizing a large number of nonlinear dynamic analyses under varying levels of ground motion intensity to systematically investigate the response of the structure (Vamvatsikosa and Cornell 2004).

In this study, performance assessment was performed according to FEMA P695 methodology (FEMA 2009) using 44 ground motions. Statistical analyses were performed on the IDA results to obtain the probability of collapse and the fragility curves for the structure. The results of the analyses are most promising in terms of the effectiveness of the structural system. The frame performed as intended over a wide range of ground motion intensity levels. Figures 7 and 8 show a sample of the results from this study. The archetype structure designed using the PBPD procedure has an excellent seismic response, with median story drift values smaller than the target 2% and 3% at DBE and MCE levels, and relatively small drift value dispersions about the medians. The results also show that the probability of collapse at the MCE level (S_a = 0.96g) is less than 10%. Overall, the deformations and the probability of collapse are within acceptable limits.



(a) DBE Level (b) MCE Level

Figure 7. Story drifts under DBE and MCE ground motions (excluding collapse cases)



(a) IDA Curves (b) Fragility Curves

Figure 8. Sample Results for the 4-Story Truss Moment Frame.

4.3 Life Cycle Costs

Initial construction and lifetime maintenance cost of the BRKB-TMF system will be analyzed using the performance assessment tool developed by Yang et al. (2009). The methodology uses the nonlinear analytical model to quantify the range of structural response expected of the structure. The results of the nonlinear dynamic analyses are integrated with the fragility functions (obtained from available test data) to identify the damage state of the structural components. Once the damage state is identified, the repair action and associate repair cost of the structural components are then calculated. The process is repeated for a sufficient number of times to quantify the performance of the structure under large array of earthquake scenarios with desired confidence. Results of the loss simulation are combined from different hazard intensities to calculate the life-time maintenance cost of the BRKB-TMF system.

5. EXPERIMENTAL STUDY

This phase of the research will be used to experimentally validate the basic underlying concept of the proposed BRKB-TMF system at the component and the subassembly levels. The research tasks for this part of the study include the following:

5.1 Evaluation of BRBs

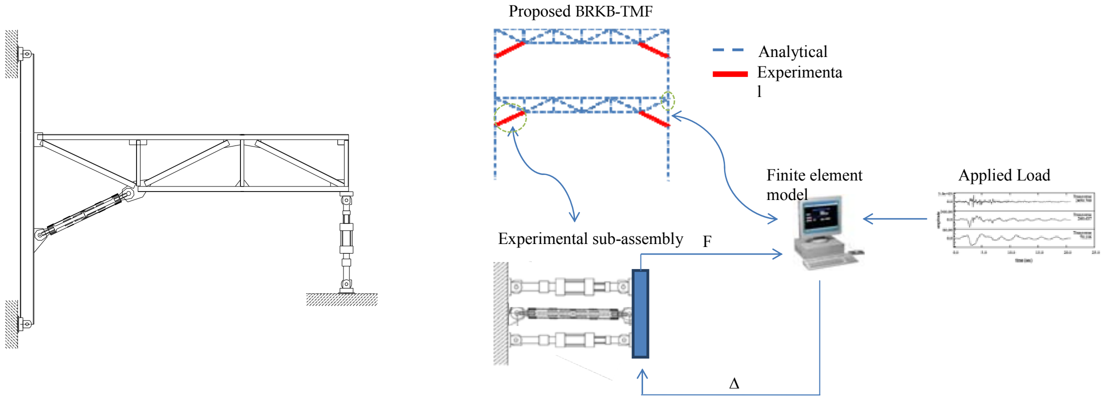
Currently, the majority of manufactured BRBs are designed and used for concentrically braced frames (CBFs). The proposed structural system for this project requires BRBs which are relatively short in length. The type of BRB required for this project is therefore not commonly available. Initial study indicated that the BRBs in the proposed structural system would be subjected to a large level of ductility demand not commonly experienced in CBFs. For evaluation purposes, an isolated BRB assembly will be tested under cyclic loading. This stage will be done to verify the ability of the BRBs to sustain expected cyclic deformation demands. In addition, the test will be used to obtain information regarding strain hardening and overstrength exhibited by the BRB. This information is essential for the design of brace connections, truss members, and the columns of the proposed frame. The test results will also be used to develop an analytical model for short BRBs for design and analysis work that will follow.

5.2 Quasi-static and Hybrid Simulation Tests

Once the performance of the BRBs has been verified, the next phase of the research will include the testing of the proposed system under cyclic load using a combination of quasi-static cyclic and hybrid simulation tests. The quasi-static cyclic test will be done on a BRKB-TMF subassemblage (Figure 9a). The objective of the test is to verify different aspects of the design concept, such as overall inelastic behavior, development of the selected yield mechanism, and interaction between the truss and the BRB. The subassemblage scale allows the test to be performed using realistic details under the expected cyclic loading. This will allow accurate assessment of component ductility. The findings will be used to refine and adjust local design details, as needed, for incorporation in the full frame design, hybrid simulation test, and full-scale frame test that will follow.

Hybrid simulation is a novel experimental testing methodology that combines the advantages of experimental subassembly testing with finite element applications to assess the nonlinear response of a complex structural system under extreme loads. Figure 9b shows the schematic of the hybrid simulation test. In this test, the columns and the trusses will be modeled using a finite element program, while the BRB will be tested in the laboratory. The finite element model will calculate the required displacement in each step and move the laboratory actuators. The forces in the BRBs will then be measured in the laboratory and used to calculate the deformation of the structure for the next integration step. This process is repeated until the end of the excitation.

The hybrid testing methodology provides many significant advantages including: 1) reductions in experiment cost, where only the portion of the structure which is expected to behave highly nonlinear (such as the BRBs) is physically tested in the laboratory, while the remaining structure is analytically modelled using finite element software; 2) physical subassemblies can be tested at large scale, because only a portion of the prototype structure is tested in the laboratory; and 3) the structures can be safely tested to extreme states, such as collapse.



a) Subassembage Test b) Hybrid Simulation Test

Figure 9. Schematic of Quasi-Static Cyclic and Hybrid Simulation Test

5.3 Full-scale Frame Test

In order to validate the effectiveness of the entire BRKB-TMF system, a full scale two-story one-bay frame will be investigated experimentally. The BRKB-TMF will be designed using PBPD method. The experimental test results will be compared with the analytical model and hybrid simulation test response results under extreme lateral loads.

A schematic view of the test frame set-up is shown in Figure 10. The truss span will be kept 9 m while the story heights are 4.2 m and 3.6 m for the ground and first story, respectively. The frame will be subjected to lateral cyclic loads at floor levels. The test specimens will be subjected to story drifts ranging from 0.25% up to 5.0%. Extensive instrumentation will be used in the BRBs, truss elements, and columns in order to monitor strains and stresses in these members. Moreover, appropriate displacement measurements will be made to monitor truss chord rotations near and away from the column face, column rotations, and joint distortions. The overall behavior of the test specimens will be evaluated in terms of load versus displacement response, stiffness and energy dissipation capacity, as well as deformation and damage in beams, columns, and connection components. The following parameters will be investigated: 1) behavior of BRKB-TMF under cyclic loading with respect to energy dissipation capacity, mode of failure and its shear yielding capacity; 2) its effectiveness in resisting extreme lateral loads; and 3) evaluation of PBPD methodology for ensuring the desired behavior including the failure mechanism.

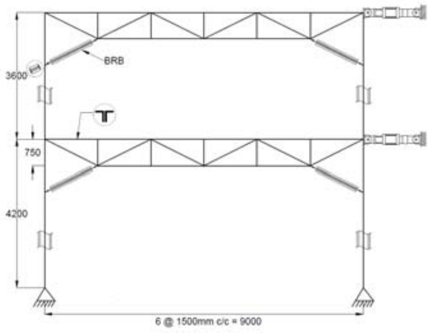


Figure 10. Full-scale Frame Test Set-up of BRKB-TMF system

6. SUMMARY AND CONCLUSIONS

This paper describes a comprehensive international collaborative research program which is being carried out to develop performance-based design methodologies for new and innovative structural systems to provide enhanced performance, safety and economy when subjected to severe load conditions. The focus in the first phase of this program is on developing innovative steel truss girder moment frames with Buckling-Restrained Knee Braces for lateral load resistance and energy dissipation under severe seismic loading. This framing system is termed as Buckling-Restrained Knee Braced Truss Moment Frame (BRKB-TMF). The research work involves comprehensive analytical and experimental investigations on the BRKB-TMF system under monotonic loading and simulated ground motions. The aims of the analytical study are: 1) to develop behavioral and performance-based models and the PBPD methodology for design of the system, and 2) to evaluate overall behavior of the system under various load scenarios. The experimental studies focus on: 1) study of member behavior, 2) evaluation of connection and subassembly behavior and 3) behavior of full-scale frames under cyclic displacements and representative ground motions.

The research work will result in a new type of Truss Moment Frame construction system capable of sustaining large lateral force demands imposed by either extreme winds, impact, or earthquakes. Moreover, the proposed framing system uses simple moment connection details, it will not only be suitable as a gravity load system, but also as lateral load moment resisting frames whose performance is augmented by BRBs. To-date, extensive frame analyses have been performed to evaluate the behavior of the proposed system under various ground motion intensities. The PBPD procedure results in the frame that exhibits excellent seismic response, with all of the inelastic activities confined to only the designated elements, the BRBs. The results of the collapse evaluation indicate that the proposed system has low probability of collapse under extreme MCE ground motions. The large-scale subassemblange tests, hybrid simulations and quasi-static BRB tests, as well as further detailed analytical studies, will provide a more thorough validation of this framing system and its design procedure for both design of new structures and retrofit of existing structures.

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