Seismic Performance of Piston Based Self-Centering Bracing System using Closed-Loop Dynamic (CLD) Testing

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ABSTRACT

Buildings with traditional structural systems experience large residual deformation after an earthquake, and often lose their serviceability and need to be demolished incurring huge economic losses. In order to resolve this issue, various smart structural systems have been developed by many researchers. One such system is the novel piston based self-centering bracing (PBSC) system. This study investigates the cyclic performance of this bracing system experimentally and numerically to predict its load-deformation response during seismic events. This newly developed bracing system employs Nickel Titanium (NiTinol) based shape memory alloy (SMA) bars inside a sleeve-piston assembly for its self-centering mechanism. During cyclic tension-compression loading, the bars are pulled from opposite directions in order to avoid compressive loading on the bars. The energy dissipation is achieved through nonlinear load deformation hysteresis. Furthermore, the PBSC bracing system is designed to be fully buckling restrained. The system exhibits flag shaped force deformation hysteresis. Displacement-based protocols generated from dynamic simulation of a 6-story building are obtained, scaled down, and applied for the fabricated brace specimen. The experimentally generated hysteresis response is scaled up and compared again to the original response in what is named closed-loop dynamic simulation and testing to reduce the time and effort of conventional shake table testing, hybrid simulation, or quasi-static testing. Reasonable agreement between the numerical and experimental results is achieved in the closed-loop dynamic testing.

Keywords: Braced frames, Self-centering, experimental, numerical, Closed-loop dynamic testing.

INTRODUCTION

A recent study conducted by the Insurance Bureau of Canada estimated the overall loss after a 9.0-magnitude earthquake in British Columbia at almost $75 billion and a $61 billion loss after a 7.1-magnitude earthquake in the Quebec City-Montreal-Ottawa corridor [1], which clearly reflects the vulnerability of Canadian civil infrastructure. To avoid such scenarios in Canada, it is imperative to take immediate measures. Since seismic load, in the form of ground shaking, generates one of the most devastating forces that our infrastructure can experience, designing structures against these large forces are often uneconomic. In various building and infrastructures, different structural elements and systems resist and dissipate earthquake-induced energy by means of deformations. Once permanent deformations take place, a structure becomes difficult to fix. After a major earthquake, these structures may have to be demolished and re-built acquiring huge economic losses. For example, in the Maule (Chile) Earthquake in 2010, the economic losses were estimated to be $30 billion (loss of infrastructure alone was $20.9 billion) which is equivalent to 17% of the GDP of Chile [2]. In the Christchurch (New Zealand) Earthquake in 2011, about $20 billion economic losses (equivalent to 13% of New Zealand's GDP) was estimated. The destruction was enormous, including demolition of around 70% of downtown buildings, loss of more than 50% of heritage structures, closure of the major business district for over 18 months, and outmigration of thousands of residents [3]. Such seismically damaged infrastructure become a major economic obligation.

Unfortunately, it is very expensive to build a structure to resist earthquake deformation in the elastic range of response. To solve this problem, self-centering devices can be used in a structure to resist the seismic load by axial action. This reduces deformation demand for the structural components and reduces their damage by a big margin. Such a self-centering device can be used in the form of bracing, and restraining device (e.g. in bridges against unseating, in buildings at beam-column joint) against earthquake movements. While considering a bracing system in a building there are various kinds available where Concentrically Braced Frames (CBFs) are considered as one of the most widely used bracing systems [4]. Unfortunately, the traditional tension compression bracing system cannot perform well under earthquake loads. Seismic load induces cyclic tension-compression load in the braces, which can cause them to buckle if buckling load exceeds at any point of time during the seismic event. After the braces buckle, the deformation of the frame increases significantly and causes the beam-column joints to go into the nonlinear range. It sometimes causes irreversible damage to the structure. Furthermore, a CBF structure is much stiffer compared to moment resisting frame counterpart. This extra stiffness attracts much more seismic load as well as floor acceleration. Excessive acceleration can cause damage to non-structural components and can also cause weakly connected non-structural components to fall on the occupants causing serious injury or fatality. In order to solve these issues, many bracing systems have been developed by researchers in the past few decades such as Buckling Restrained Bracing (BRBs) [5], CastConnex Scorpion Yielding Brace [6], Memory Alloys for New Seismic Isolation Devices (MANSIDE) project braces [7], and Self Centering Energy Dissipation Device (SCED) [8]. All the adopted methods were targeting enhanced seismic performance of buildings in terms of maximizing energy dissipation and minimizing residual drifts. All the developed systems showed good aspects in terms of self-centering, efficient energy dissipation and flag shape hysteresis response. However, in the field of self-centering bracing systems, issues related to complexity and availability of some material still presents a challenge. In this paper an attempt is made to solve this issue by developing a self-centering bracing system that eliminates residual deformations and is relatively easy to construct.

On the other hand, in the field of structural testing, hybrid simulation has advantages over pure numerical simulation as it addresses modeling uncertainties by replacing components that are difficult to model with physical specimens. The hybrid simulation also addresses many of the limitations associated with conventional testing methods such as the shake table test (STT). For example, since only a small portion of the structure needs to be physically constructed for hybrid simulation, it is much more economical than STT. Furthermore, the size and weight restrictions present in STT are generally high. In hybrid simulation, size is only limited by the amount of available space in the lab, and weight is only limited by the capacities of the strong floor and reaction frame. Hybrid simulation has advantages over quasi-static test (QST) as well since inertial and damping effects can be captured, and interactions between the specimen and the rest of the structural system are accounted for, which is critical for evaluating the dynamic behavior of structural systems subjected to earthquake loading [9]. Despite the long history, there remain many challenges in structural testing that are relevant to the physical components of hybrid simulation. These challenges include, but are not limited to, multi-degrees-of-freedom control; control of rotational degrees-of-freedom; testing of extremely rigid specimens; measurement of large deformation with geometric nonlinearities, etc., and lastly the high cost associated with shake table testing and hybrid simulation [10].

In this study, a simplified testing and simulation method is proposed in order to overcome the drawbacks of STT and conventional hybrid simulation approach especially when limitations in terms of time and testing facilities exist. The proposed methodology executes the steps of conventional hybrid simulation in an off-line mode saving a huge amount of time and effort. A similar methodology has also been used by other researches in the past, where the loading input for the specimens of their interest was extracted from an accurate dynamic analysis of the entire structure [11,12,13]. In this method, displacement-based loading protocols of a structural component are generated from several dynamic simulations of a full-scale model structure in finite element environment if it can accurately simulate its seismic response. Then the structural component is physically tested using the extracted loading protocols and boundary conditions to determine its seismic behavior. The loading protocol could be scaled-down based on the requirements and lab limitations. Here, a 6-story building equipped with novel Piston Based Self-Centering (PBSC) system is analyzed under different ground motions. The displacement-based loading protocols are obtained, scaled down, and applied to the physical brace specimen. The experimentally generated hysteresis response is scaled up and compared again to the original response in what is called closed-loop dynamic testing. The entire testing methodology is carried out in a closed loop environment to validate its reliability. The proposed methodology holds the advantage of hybrid simulation in terms of accurate integrated experimental testing of a real specimen with refined numerical model and the advantage of quasi-static and dynamic testing in terms of reduced time and effort needed for the investigation. The novel PBSC system is developed using a device commonly seen in mechanical systems, which is a cylinder-piston assembly. Using this assembly, a brace member can carry a large magnitude of tension and compression forces where Nickel Titanium (Nitinol) based shape memory alloy (SMA) bars inside a sleeve-piston assembly for its self-centering mechanism are utilized. Stable and self-centering hysteresis behavior is achieved when the system is subjected to qualifying quasi-static loading. The main objectives of this study are to determine the performance of the proposed bracing system under seismic load and validate the applicability of the closed-loop dynamic testing approach. Initially, the bracing element was fabricated and then tested using the universal testing machine under qualifying quasi-static loading protocol. In this paper, the concept of closed-loop dynamic testing is described and the application of this technique on the developed system is presented. The generated hysteresis curves from closed-loop dynamic testing for the new system are also presented and its performance is discussed. Reasonable agreement between the numerical and experimental results is achieved in the closed-loop dynamic testing.

DESCRIPTION AND DETAILS OF THE SYSTEM

The idea for the PBSC device is anticipated to work mainly in a Chevron/V/X configuration bracing in buildings as shown in Figure 1a. This system can be employed for new and existing both steel and concrete structures. Other applications include a single configuration as bridge restrainer, or parallel to the beam and attached to the beam and bracing which works like a shear panel device. Also, a parallel configuration attached to top and bottom flange of beams at the beam-column joints in buildings.

The proposed system is employed using a device commonly seen in mechanical systems, which is a cylinder-piston assembly. As shown in Figure 1a, the tensile and compressive strength of a brace should be almost equal. The brace's design strength should be kept below the buckling and yield capacity of the shaft. In order to limit compression load in an individual brace, the shaft and tie arrangement shall be constructed as a piston system where the ties and part of the shaft shall be held inside a larger metal sleeve (Circular, square, rectangular or any other geometric cross section). For fabrication purposes, design drawings including the details of the PBSC arrangement are given in Figure 1b. In this system, separate ties are used to connect front plate to piston plate and back plate to piston plate. Both ends of the sleeve shall have thick metal caps to provide support for the front ties (when the whole system is under tension) and the back ties (while the system is under compressive load).

Two sets of ties (front and back) are connected at the shaft end plate and the other ends of the ties are connected to the cylinder/sleeve end plates using movable joints. The movable joints are constructed in such a way that they only allow the ties to go out. Inward movement of the ties will be allowed up to the ties end points. Locks/couplers placed at the tie ends are introduced to prevent the ties from fully entering the cylinder/sleeve. This way brace tensile and compressive loads will go through the front and back ties alternately during cyclic loading. The joint between ties and the plates also allows rotational movement without any moment generation (hinge joint). This will ensure bar straightness in the event of any kind of plate bending. The piston plate is made slightly smaller in size than the sleeve's inner dimension so that plate bending/rotation during loading does not affect the sleeve. The ties are designed for a load lower than the buckling and yield strength of the shaft and the cylinder/sleeve. When the system is under compression and the load reaches the yield load of the ties, the ties will yield and deform significantly thus lowering the axial stiffness of the system. This will, in turn, limit the axial force of the system and keep it below the buckling capacity of the shaft. In this study, the ties are made of super elastic shape memory alloy (SMA) (i.e. NiTinol) bars. Super elastic SMA bars are known for their unique property of regaining original/undeformed shape upon load removal [14,15]. The use of super elastic SMA bars will ensure the full self-centering capability of the brace [16]. The dimensions of the different components of the systems are shown in Figure 1a.

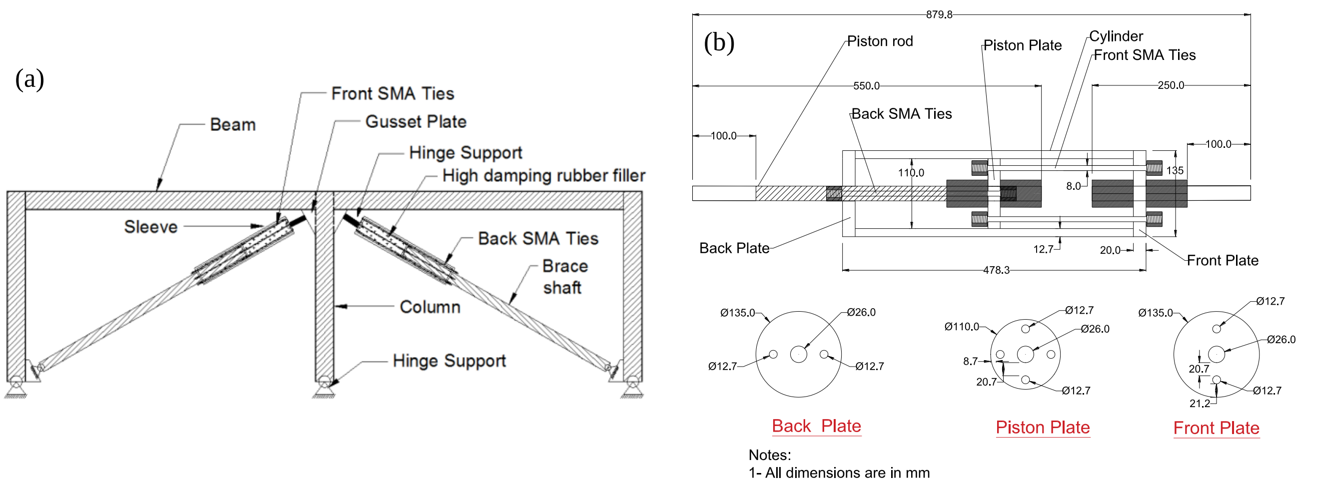

Figure 1. (a) Basic Components of a Piston Based Self-Centering brace, (b) PBSC brace components

Specimen Details

The fabrication process of the PBSC brace specimen is carried out by firstly generating 3D models including the different components. Alternatively, the structural details of the cylinder, piston and internal components, once the brace is fully constructed, are shown in Figure 2. As shown in the latter figure, the lock nuts are installed and tightened enough to prevent the SMA rods from sliding or moving in any direction. However, this tightening was applied manually so that no significant tension force is applied to the SMA. Noteworthy, the outer body cylinder of the specimen, as well as, the supporting discs are fabricated using 12.7mm thick steel cylinder and plates, respectively. It is critical to keep the supporting components of the system strong enough and in the elastic range as the SMA rods reach their maximum load carrying capacity. Weak components, especially the outer encasing cylinder, can experience some permanent deformations which defy the entire concept of the self-centering device. The bracing system is buckling restrained. The SMA rods in the device are configured such that they will always experience tension regardless whether the brace, as a whole, is under tension or compression. The nuts that are installed at both ends of each SMA rods transfer the tension load through bearing between the nut and the plates. When the brace is under tension, the front ties bars get locked with the front cap by the couplers/nuts and are under tension whereas the back ties are not engaged and released from loading. Under compression, i.e., when the shaft moves inside the piston, only the back ties are engaged and under tension whereas the front ties do not experience any load. In each cycle when any of the two tie bars are under tension, the other two are released (compression-free) as they don't have nuts restraining them in the other direction. Thus, the device acts a buckling restrained brace system.

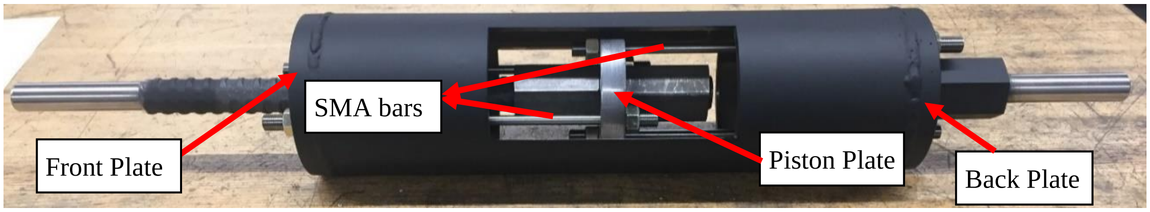

Figure 2: PBSC brace specimen

EXPERIMENTAL INVESTIGATION

The objective of the experimental program was to investigate the cyclic behavior of bracing members in concentrically braced frames by means of cyclic axial tests. Quasi-static tests were carried out at the Applied Laboratory for Advanced Materials and Structures (ALAMS) at the University of British Columbia (UBC)'s Okanagan campus. The specimen was tested using the MTS universal testing machine with a capacity of 500 kN. Taking into consideration the machine dimensional limits and characteristics, together with ease of specimen handling, the experimental set-up described in Figure 3 was adopted.

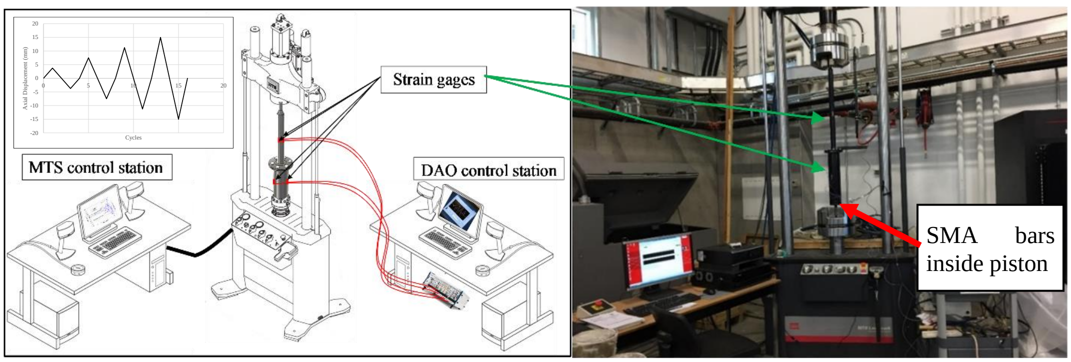

Figure 3: Test setup

MTS control system and the data acquisition system were both connected to the specimen to measure the different test parameters. The MTS machine is equipped with a load cell to measure the axial force as well as vertical movement transducers to measure the movement of the MTS head. Additionally, four SMA strain gauges in total were attached to the four SMA rods to get more insights into the stress-strain behavior of the SMA bars, as shown in Figure 3. The time history with a maximum value of 15mm was associated with the moving head of the universal testing machine. A maximum value of 15mm is considered so that the maximum strain in the SMA rods does not exceed 6%. This type of Nickel-Titanium base SMA rods experiences some residual deformation after exceeding this threshold. Employing the above test setup and the loading protocol, the cyclic test was conducted. Figure 4(a) depicts a stress-strain plot obtained for one of the SMA rod specimen obtained from the right top bar in the device. Marginal residual deformation was observed in the test result. Stable and symmetric self-centering hysteresis loops were obtained as shown in Figure 4(b). The PBSC brace showed negligible permanent deformation throughout the entire testing procedure. As mentioned previously, the permanent deformation can be avoided by applying deformations that do not exceed the SMA superelastic threshold. Therefore, a design engineer should consider such criteria when designing this bracing system. The SMA bar lengths should be selected based on the expected maximum deformation that the brace will experience during the design seismic event. However, it does not have a significant impact on the overall performance of the brace element.

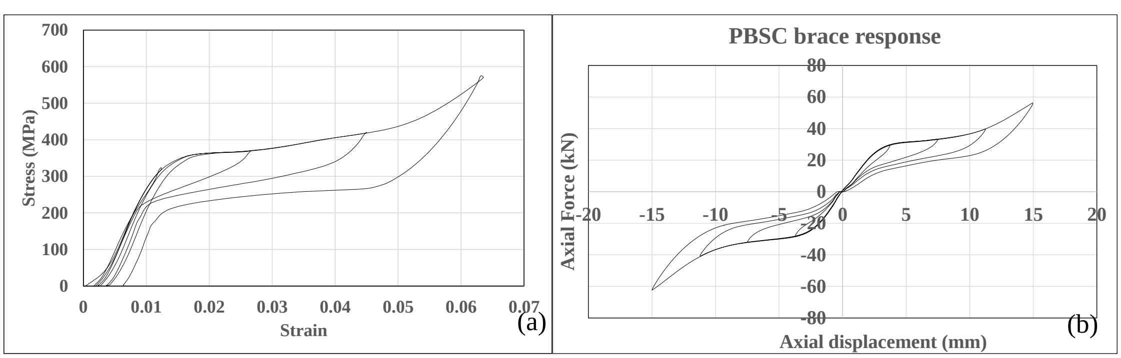

Figure 4: (a) Stress-Strain response of a single 8 mm diameter SMA bar, (b) Hysteretic response of the PBSC bracing system

CLOSED-LOOP DYNAMIC TESTING

The concept of closed-loop dynamic testing is proposed to validate its feasibility of conducting comprehensive dynamic testing on members without the need to conduct the braced frame testing under quasi-static test or using hybrid simulation. Hybrid simulation is a testing method for observing the seismic response of structures using a hybrid model included of both physical and numerical substructures. Because of the unique feature of the method to combine physical testing with numerical simulations, it provides an opportunity to investigate the seismic response of structures in an efficient and economically feasible manner. The closed-loop dynamic testing, however, reduces the time and effort furthermore compared to conventional quasi-static testing of braced frame and hybrid simulation. In this section, the concept and the validation of this new concept are presented.

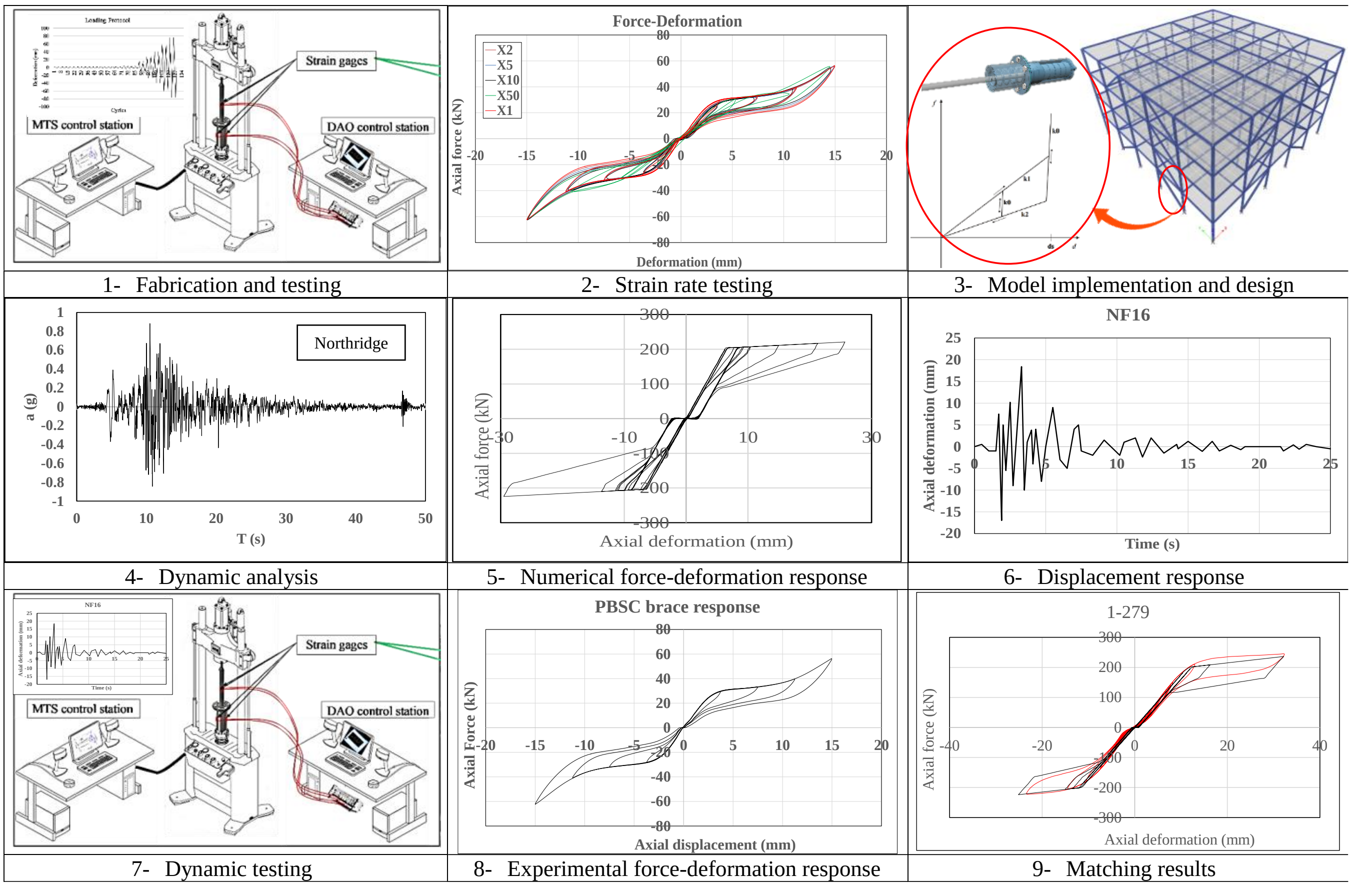

Figure 5: Closed-loop dynamic testing flow chart procedures

The flowchart diagram presented in Figure 5 represents the concept adopted in this study for the proposed closed-loop dynamic testing approach. The concept involves nine main procedures: (1) Generate design drawings and fabricate a small scale specimen then test it under qualifying quasi-static loading protocol, (2) Conduct a series of experimental tests using varying loading rates to study the strain rate effect on the system, (3) Implement the hysteresis behavior obtained from experimental testing in a finite element environment and design building equipped with the PBSC, (4) Apply the dynamic load on a frame building equipped with the PBSC system, (5) Generate and extract the force-deformation hysteresis response of the brace element of interest, (6) Extract the brace deformation response as a function of time, (7) Scale down the deformation response, using the similitude laws, and apply it to the scaled-down brace specimen, (8) Extract the force-deformation hysteresis response from the test program, and (9) Scale up, using the similitude laws, the deformation response and match it with the original response obtained from the dynamic simulation of the frame building. In details, step 9 looks at a match between the scaled experimental results and the response from the model. It is refinement procedure to achieve better matching of the results in the closed-loop dynamic testing, which is considered as a refined model after adjusting the parameters. By conducting the above-mentioned procedures, the system response is studied and validated from start to finish in a closed loop as shown in Figure 5. The above-mentioned procedures are implemented using three earthquake ground motions and applied consecutively on the brace specimen. The details of the applied deformation-based loading protocols and the obtained results are presented in the following section.

One of the important aspects that closed-loop dynamic testing can offer is the validation of a new structural system in seismic regions. This is especially true when a recently proposed system or device is going to be employed in a structure. Closed-loop dynamic testing approach can provide a cost-effective solution in a timely manner for a new system. In this approach, the designer can fabricate the new structural component, test it under various strain rate to understand its dynamic response and validate the results numerically. Having an experimentally verified model will help the design engineer to design a structure equipped with this new system and reassess the design using the closed-loop dynamic testing. For different seismic design parameters and zones, representative earthquake records can be used to perform the dynamic response validation process.

A six-storied tall, 4x4 bay steel braced frame was considered in this study. The selected 6-story building represents a typical residential/office building that is widely found in the city of Vancouver, and it is typical in such building heights to use bracing as the lateral force resisting system [17]. The bay widths are 5m and story heights are 3m each. Therefore, the total width of the building in two orthogonal directions is 20m, and the total height is 18m. The braces are only installed on the perimeter frames of the building as shown in Figure 6. To design the braces for full lateral-load arising from the seismic events, all beams were connected to the columns using moment released connections; and the columns were restrained to the foundation using hinges. Yet, the columns were modeled as continuous members along with their heights. The modeling was done in a way that the structure becomes unstable under lateral loading if braces are not installed. The braces were modeled using pin ended connections and were installed as inverted "V" in the middle two bays. In this configuration, only the braces will resist the lateral load arising from the earthquake. The slabs were modeled using 150mm deep concrete shell sections. However, for clarity, it is hidden from the view in Figure 6. The details of designed building can be found in [18].

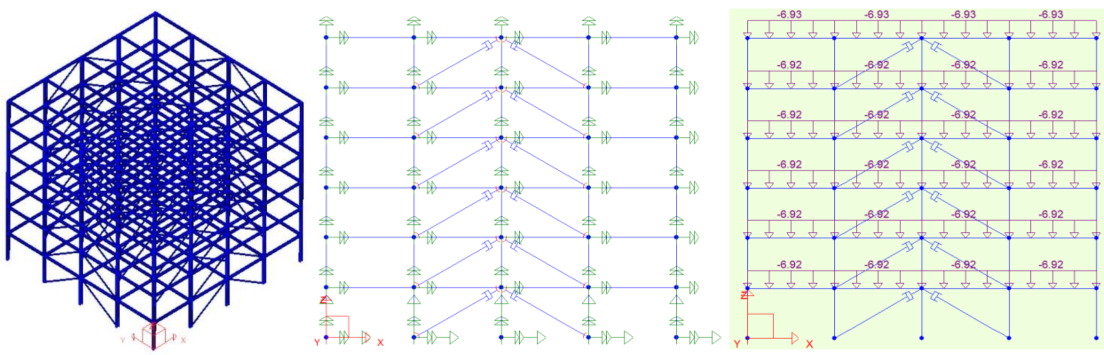

Figure 6: Three-dimensional model of the steel building, Nodal Restraint Conditions, and Uniformly distributed gravity loading on the beam for the 2D model (from left to right)

Table 1: Spectral acceleration values for Vancouver Soil Class "C"

Sa(T)	Sa(0.2)	Sa(0.5)	Sa(1.0)	Sa(2.0)	Sa(4.0)
Acceleration (g)	0.95	0.65	0.34	0.17	0.085

The dashpot shapes shown at the end of the braces represents the zero-length link elements. To calculate the hysteresis model's input parameters, three different PBSC braces were designed for the three different brace sections used in this frame. In order to design the PBSC braces, the ultimate design loads which were used to design the brace sections were retrieved from the S-FRAME Software. The envelopes of all the design load cases were taken and the PBSC brace was designed for it. The amount of required SMA needed for each brace was calculated using a spreadsheet specifically developed for this task. The PBSC brace design process used in the spreadsheet is as follows: the ultimate design load was divided using the austenite to martensite starting stress (σ_{ams}) of SMA to find out the required cross-sectional area of SMA bars. For this study, the value of σ_{ams} was taken as 400 MPa. The result gave the necessary cross-sectional area of the SMA bars. Bar diameters were selected in a way to provide an integer value or as close to that as possible. In the next step, a design length of the SMA bars was chosen. The estimated length of the SMA bars was taken as 1/6th of the brace length or approximately 1m. This ratio has been selected based on the following assumption: buildings are generally designed for a maximum interstory drift of 2%-2.5%. As braces are diagonal members, they typically experience 40%-50% of this drift in their axial direction; which results in a drift of approximately 1%. As NiTinol based SMAs can recover from 6%-9% strain [19], we can comfortably make the NiTinol bars of the PBSC brace 1/6th to 1/9th of the total brace length. This will also result in a lot of material and cost savings. The hysteresis results were used to find out the initial and post-yield stiffness as well as the SMA unloading stiffness. These values were provided as input in the S-FRAME Software link hysteresis input window. This process was repeated three times for the three brace sections, and three links were generated. Finally, these links were assigned to the appropriate brace ends. Figure 7 shows the link input parameters used for the HS127x8 brace section.

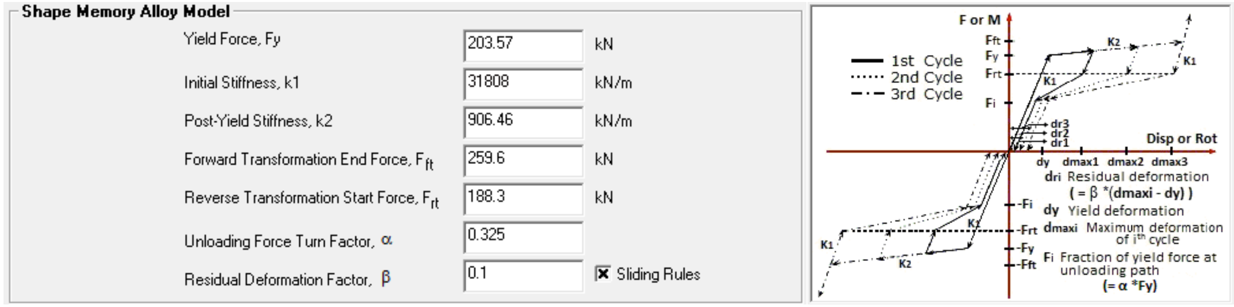

Figure 7: Sample input data for PBSC link hysteresis

The highest base shear is mainly observed in the lowest story next to the ground level where braces will experience the highest force-deformation demand. A bracing element located in the first story is, therefore, considered to conduct the closed-loop dynamic testing. Three random earthquake records obtained from the Pacific Earthquake Engineering Research Center (PEER) Next-Generation Attenuation (NGA) database and matched with the UHS of Vancouver, are selected where they had different deformation response on the brace element. Some of these deformations have a high-frequency response and some have low frequency. Having different deformation frequency responses will help characterize the dynamic behavior of the brace specimen and study the strain rate effect, under dynamic loading, on the system. Once the deformation responses have been obtained, they were scaled down based on the scaling factor of ¼. According to scaling laws, the deformations were divided by 4 and the time was divided by two (i.e. $\sqrt{1/4} = 1/2$). The next step is to simplify the response into segments that can be input into the MTS control system. The different loading rates for each segment, based on the deformation and time, is also calculated and incorporated into the protocol to closely simulate the dynamic effect. Accurate representation of the real response was achieved by transforming every deformation response precisely. It is worth mentioning, once the protocols have been defined, the tests are conducted successively on the specimen without altering in position, tightening of the bolts, and any form of maintenance.

Based on the obtained experimental results, the numerical module in S-FRAME is modified and the dynamic analyses are re-conducted. Due to the discrepancy is the simplification of the stress-strain curve of the Nitinol which does not capture the nuances of the response, several trials were conducted by adjusting the model parameters in order to achieve more comparable results. The refined results are obtained, compared and presented in Figure 8 where much better agreement is achieved. The results presented in Figure 8 highlights the feasibility of the proposed closed-loop dynamic testing approach. However, care should be practiced when adopting this technique. In systems where strain rate effect is highly noticeable and observed, the closed-loop dynamic testing can provide a similar validation like the one presented herein if the model can accurately capture the strain rate effect. Similar results were achieved on a comparable bracing system which can be found in [20]. The further experimental investigation can be implemented on different systems to generalize the concept. Nevertheless, for systems with behavior like PBSC, this technique can be an affordable option to validate the design process and the feasibility of adopting new systems.

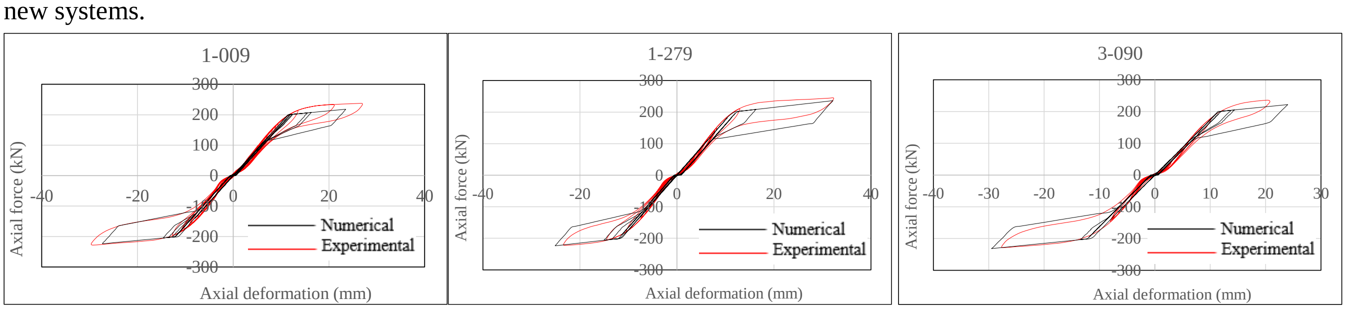

Figure 8: Experimental and numerical hysteresis response for the 3 records using the closed-loop dynamic testing

CONCLUSIONS

This paper described the development and seismic performance assessment of a novel Piston Based Self-Centering bracing system for the civil engineering structures. Design drawings were generated, and a test specimen was fabricated and tested several times under quasi-static loading protocol where stable and self-centering hysteresis behavior was achieved. The generated hysteresis curves for the new system were presented and its performance was discussed. This paper also described a new testing and simulation technique in order to reduce the computational and experimental requirements and efforts in structural experimentation and validation. In this approach, displacement-based protocols generated from dynamic simulation of a 6-story building equipped with PBSC system were obtained, scaled down, and applied for the fabricated brace specimen.

The experimentally generated hysteresis responses were scaled up and compared again to the original response to fully close the loop and validate the test procedure, which is named as closed-loop dynamic testing. The proposed closed-loop dynamic testing technique was adopted and conducted on the frame building equipped with the PBSC system. The dynamic deformation response was obtained, scaled down, and applied to the fabricated specimen. The new closed-loop dynamic testing technique proved to be reliable where reasonable agreement between the dynamic simulation and the experimental results was achieved. This proposed method minimizes the time and computational efforts required compared to shake table and hybrid simulation testing method. The proposed system overcomes the other available self-centering systems in its simplicity and constructability. Such bracing will not only be an efficient technique for new buildings but also for retrofitting older deficient structures.

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