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A HYSTERESIS MODEL FOR THE PISTON-BASED SELF-CENTERING BRACING SYSTEM CONSIDERING RESIDUAL DEFORMATION

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ABSTRACT

A load deformation hysteresis model has been developed for the piston based self-centering (PBSC) bracing system. This bracing system utilizes shaft-piston mechanism for transferring load to its core energy dissipating elements, which are made of Nickel Titanium alloy (NiTinol) bars. These bars provide the brace its strength as well as the self-centering capability. Although in theory, the NiTinol based shape memory alloy bars are supposed to come back to their original shape after large nonlinear deformations, in reality, they experience residual deformation. The hysteresis models, which are currently available for capturing the behavior of self-centering systems, are known as flag shaped hysteresis. Unfortunately, these flag shaped hysteresis models cannot capture residual deformation. In order to solve this issue a novel hysteresis model has been developed for the PBSC bracing system. This model will enable researchers to capture the PBSC brace behavior in detail during quasi-static and dynamic time history analysis. This hysteresis model is developed using the results of nonlinear static analysis in MATLAB. The resultant plots were thoroughly examined to determine loading/unloading rules. These rules were coded and implemented in the S-FRAME software's nonlinear analysis solver. A building frame model was built with PBSC bracing system and it was tested using ten earthquake records scaled to Vancouver soil class "C" response spectrum. It was observed that the PBSC brace has an excellent re-centering capability.

Keywords Self-Centering Brace, SMA Brace, NiTinol, Seismic

1. INTRODUCTION

Recent seismic events and vast damages in Nepal (25th April 2015), New Zealand (22 February 2011), Chile (27th February 2010) has renewed interest in self-centering structural systems. These systems in theory are able to re-center after large nonlinear deformations. Hence, after a significant earthquake it is expected that such systems will be able to come back to their original state; and thus will be able to reduce permanent damages and prevent post-earthquake collapses. So far, researchers have developed various self-centering devices, such as: PBSC (Haque & Alam, 2014), SCED (Tremblay & Christopoulos 2012), MANSIDE (Dolce et al. 2001, Dolce & Cardone (2006)), RHDB (Zhu and Zhang (2007)) and Self-centering buckling restrained brace (Miller et al. (2012)). Most of these systems rely either on high-strength steel strands/composite cables or on superelastic shape memory alloy (SE SMA) wires/bars. Their use can result in very low (less than or equal to 0.1% as per Zhu and Zhang (2007)) residual interstory drift ratio for the host structures. Among these, the SE SMA is a thermomechanical alloy made of an equal molecular ratio of Nickel and Titanium. At room temperature, the SE SMA is able to regain its original shape after large nonlinear strains (6%-8%). This unique property has made it one of the most fascinating materials in the development of smart structures.

Although, there are some fundamental differences between the above-mentioned braces, they exhibit almost similar force deformation response; which are generally flag-shaped. Although, these systems are declared as "fully self-centering", in reality, they experience some residual deformation; which arises mostly due to the residual deformation observed in the material used in these systems. The flag-shaped hysteresis models available in Opensees or Ruaumoko cannot simulate the residual deformation properly. Without this feature, the structural engineers will not be able to accurately determine the performance of their designed structure.

In the previous study (Haque and Alam, 2015), the authors have presented the PBSC brace hysteresis without considering the residual deformation of the SMA tie bars. It was found that without considering SE SMA's residual deformation, the PBSC brace hysteresis would be similar to the SMA flag hysteresis. However, it was found out that the PBSC bracing system has a unique hysteresis if residual strain is considered for the SE SMA material. In the following section, this is discussed in detail.

1.1 PBSC Brace

The piston based self-centering bracing system is a novel invention by Haque and Alam (2014). This system is essentially composed of a piston, shaft and SE SMA bars. Nickel titanium based shape memory alloy bars are used for transferring axial load from the shaft to the connected structure directly or through the sleeve for tension or compression forces, respectively. From the detailed solid model based analysis done in ABAQUS (2014), it was found that the brace has a hysteresis response almost similar to the flag shaped hysteresis (Haque and Alam, 2015). As mentioned earlier, this hysteresis shape signifies excellent self-centering capability.

2. SMA BAR BEHAVIOUR

As the PBSC brace utilizes SMA bars, it is essential to understand the cyclic loading unloading response of these bars. DesRoches et al. (2004) has carried out quasi-static and dynamic cyclic load tests on SMA large diameter bars. He observed that SMA bars show a good re-centering capacity (Figure 1). The residual strain observed for the test specimen was approximately 0.65% where the maximum strain was 6%.

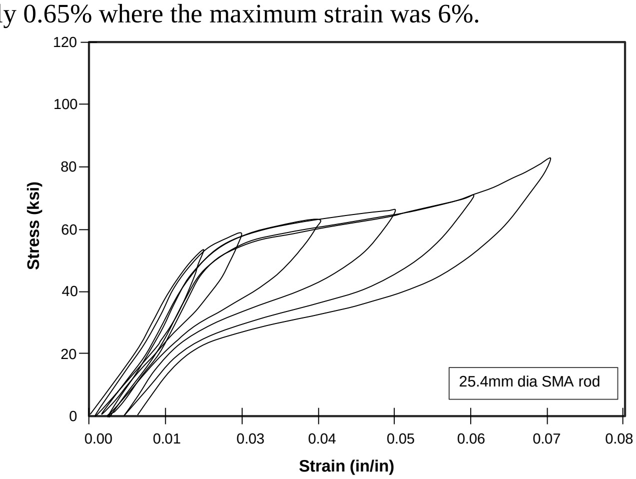

Figure 1: Stress–strain plot for 25.4 mm diameter nitinol SMA bar subjected to quasi-static cyclic loading (adapted from DesRoches et al. 2004).

From Figure 1, it can be seen that SMA cannot fully re-center. The residual plastic deformation is a function of the maximum plastic deformation. The current SMA material model (Auricchio and Sacco (1997)) is not capable of capturing this behaviour. In order to solve this issue, a new uniaxial SE SMA material model has been developed. This model follows the basic hysteresis rule established by Auricchio and Sacco (1997). In addition to that, it can simulate the residual strain accumulation. However, this modified model is only for representing the super elasticity. This model cannot be used for the shape memory effect or solid element modeling.
In the PBSC bracing system the SE SMA bars only gets loaded in tension, therefore an SE SMA material model with only tension loading unloading rule is sufficient in simulating the brace behaviour.

3. PBSC MODEL SIMPLIFICATION

In order to model the PBSC bracing system in MATLAB finite element program, several idealization and model simplifications were carried out. Below is a systematic description of the process by which the model was simplified.

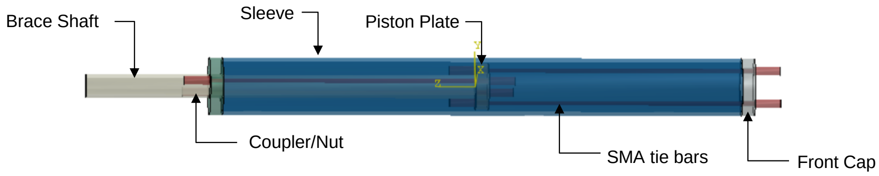

Figure 2: Longitudinal profile of the PBSC bracing system

It can be seen from Figure 2 that the PBSC bracing system has three major components: the shaft, the sleeve and the internal SMA tie bars. The plates are for transferring loads from one of these parts to the other. From this figure, it can be understood that the sleeve is acting as a support for the back cap/plate, which transfers load from the SMA bars to the support when the brace is under compressive loading. Furthermore, the sleeve cross section is designed to be much larger than the ties and the shaft; this ensures very low longitudinal deformation for the sleeve. Therefore, a finite element model made without the sleeve should behave almost similarly if the plates are restrained from movement.

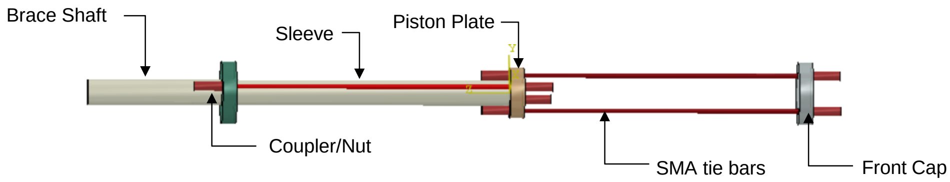

Figure 3: PBSC bracing system without the sleeve

Figure 3 shows the concept of the PBSC brace model without the explicit sleeve model. For MATLAB implementation, we further assumed that both the shaft and the SMA bars are bar elements and the plates are the nodal points. This simplified model is shown in Figure 4.

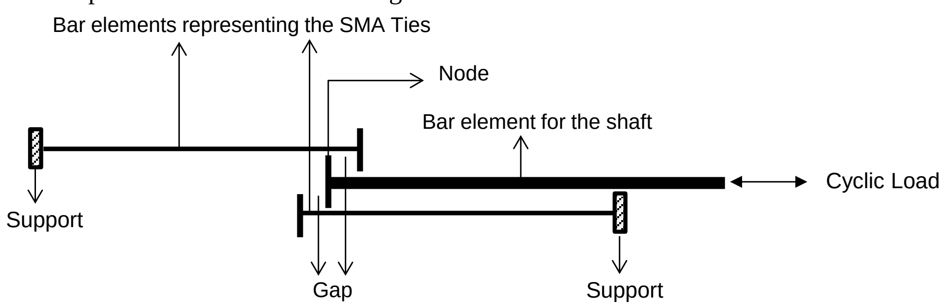

Figure 4: Simplified PBSC brace model

4. SMA MATERIAL MODEL

In this study, at the first step, a tension only cycle based SE SMA material hysteresis model was developed. Then it was incorporated into a MATLAB finite element program specifically developed for the quasi-static analysis of the PBSC bracing system developed using the simplified model shown in Figure 4. This section briefly discusses the rules of SE SMA material model with residual deformation.

The tension only hysteresis model of the SE SMA hysteresis model is shown in Figure 5. Here σ_{ams}, σ_{amf}, σ_{mas} and σ_{maf} represent the austenite to martensite starting stress, austenite to martensite finishing stress, martensite to austenite starting stress and martensite to austenite finishing stress respectively. E_i, E_p and E_v represent the initial plastic and variable modulus of elasticity. ε_{ri} represents the residual deformations for the corresponding cycles.

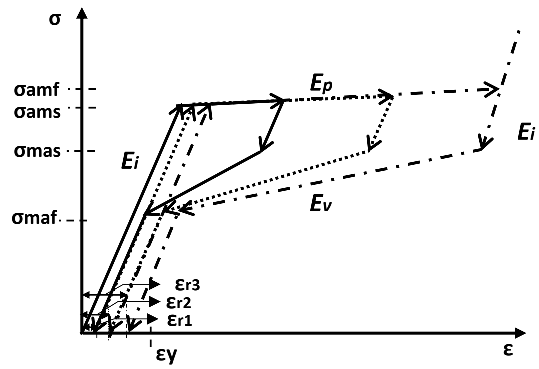

Figure 5: SMA uniaxial stress-strain hysteresis model with residual deformation (Tension Cycles Only)

The residual strain is calculated using equation (1). For simplification, a linear relationship has been used between the residual and plastic strain.

[1] Residual strain = (Maximum strain of the cycle-Yield Strain)*Residual Strain Coefficient

Here, the "Maximum strain of the cycle-Yield Strain" is the plastic strain for the current cycle under consideration. Furthermore, the Yield Strain is calculated based on the original backbone curve. In this hysteresis model, residual strain is only allowed to increase. Therefore, if current cycle has a maximum strain value less than the maximum strain of one of the previous cycles, the new residual strain will not be calculated and the previous residual strain will be used for the current cycle. Because of this rule, if the material experiences large strain cycles at the beginning, the residual strain will be set to a higher value and will not be reduced if the subsequent cycle's maximum deformations are smaller. Furthermore, every subsequent cycle starts from the previous maximum residual strain point (ε_{ri},0) on the strain axis.

The residual strain coefficient can be set to any value between 0 and 1. However, a value of around 0.1 (10% residual strain coefficient) is most practical for NiTinol based SMAs which can be seen from Figure 1.

The SE SMA hysteresis model shown above was coded as a function in MATLAB (2012). This function was called from the MATLAB finite element program. A bilinear kinematic material model was used for the steel shaft. A quasi-static loading history was provided as input and at every load step both of these material models were called to calculate element stiffness matrices from the corresponding material tangent modulus. The global stiffness matrix is formed and the global deformation matrix is calculated using the global force matrix. The brace geometry is updated and the program retrieves the next loading data from the memory. Due to the use of SMA material model with residual deformation, the tie bars are subjected to plastic deformation, which changes their lengths permanently. When the load reverses from either tension to compression or vice versa, the elongated lengths are kept in the memory for the unloaded tie and the same is loaded for the newly loaded tie. When the new length data is retrieved, a sudden length change occurs inside the brace, this generates a displacement data without any force. This results in a sliding response in the hysteresis shape.

5. QUASI-STATIC RESPONSE FROM MATLAB

Based on the procedure described above, a load controlled quasi-static analysis was carried out on the PBSC bracing system. The following section property data was used for this analysis. Shaft is made of HS219x9.5 section with 4m length and ties are 20mm diameter bars with 1m length. The shaft is made of 350MPa steel and the tie bars are made of SMA. For the tie bars the following SMA material properties were used: σ_{ams} = 400MPa, , σ_{amf} = 510MPa, , σ_{mas} = 370MPa and σ_{maf} =130MPa. The modulus of elasticity for SMA was set to 62.5 GPa and for steel it was set to 200GPa. The plateau strain was assumed to be 6% and the residual to plastic deformation ratio was set to 0.1 or 10%. Using the above mentioned section properties and the loading history data shown in Figure 6(a), a quasi-static analysis was carried out. Figure 6(b) shows the global load deformation hysteresis response of the brace. The previously mentioned sliding behaviour can be observed near the origin. This is generated due to the 10% residual to plastic deformation ratio included in the SMA material model. It can be seen that with residual deformation taken into account the brace shows different behavior compared to the one without residual deformation presented in Haque and Alam 2015.

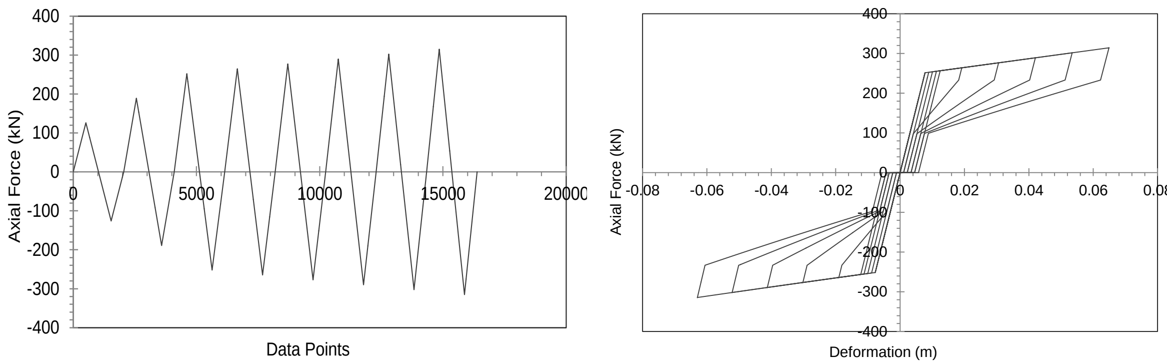

Figure 6: (a) Input loading history and (b) Hysteresis response of the PBSC bracing system from MATLAB finite element model

6. HYSTERESIS RULES

Based on the observed response Figure 6(b), an SMA flag hysteresis rule has been developed for simulating the PBSC bracing system. This modified rule of the SMA flag hysteresis with sliding deformation is graphically presented below. In this hysteresis model, residual deformation values are calculated every time a deformation cycle exceeds the previous maximum deformation in the respective direction. This means that positive and negative deformations are independently calculated and they do not affect each other. The residual deformation "d_r" is calculated using the following equation.

[2] d_r = (Maximum deformation of the cycle-Yield deformation)*Residual deformation Coefficient

Figure 7 depicts the proposed PBSC brace hysteresis model with sliding deformation. Three consecutive cycles have been shown here with loading/unloading directions marked with arrows. Here k_1, k_2 and k_v represent the initial, post yield and variable unloading stiffness's. F_{ff} represents the force at which austenite to martensite transformation finishes and F_r represents the force where SMA starts transforming from martensite to austenite. d_{r1}, d_{r2} and d_{r3} represent the residual deformation of cycle 1 to cycle 3 respectively.

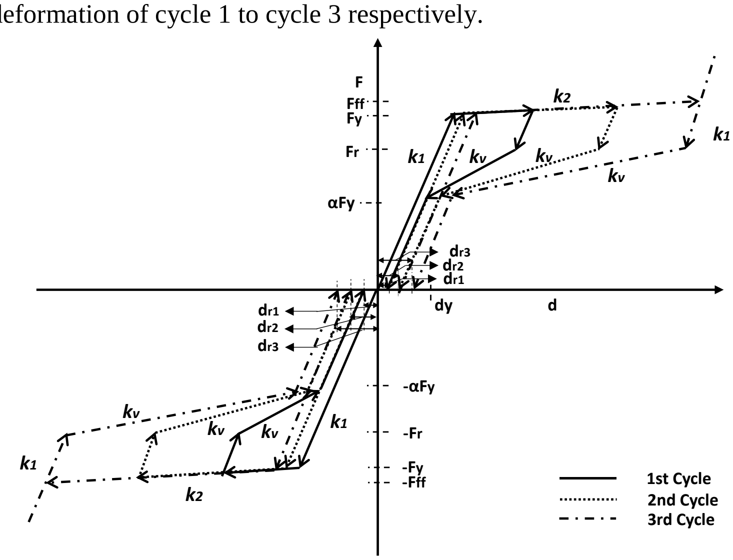

Figure 7: SMA flag-shaped hysteresis model with sliding response.

The hysteresis rule presented in Figure 7 was integrated in S-FRAME software's nonlinear solver for analyzing building frames equipped with PBSC bracing system.

7. ANALYSIS MODEL

A six-storied tall, 4x4 bay steel braced frame was considered in this study. 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. In order to design the braces for full lateral load arising from the seismic event, all beams were connected to the columns using moment released connections. The columns were restrained to the foundation using hinges. However, the columns were modelled as continuous members along 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 modelled 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 thick concrete shell sections. However, for clarity it is hidden from the view in Figure 8. The following loading was applied to the floor slabs (except the roof) in gravity direction. Superimposed dead load: 2kN/m^2, live load: 2.4kN/m^2. On the roof, the dead load was considered as 0.5 kN/m^2 and snow load was taken as 2.2 kN/m^2. Furthermore, another 0.9kN/m^2 on the roof was considered for miscellaneous storage loads. After the structural modeling, the frame was analyzed under both gravity and seismic loading. The seismic zone considered for this analysis is "Vancouver". The soil class was taken as class "C".

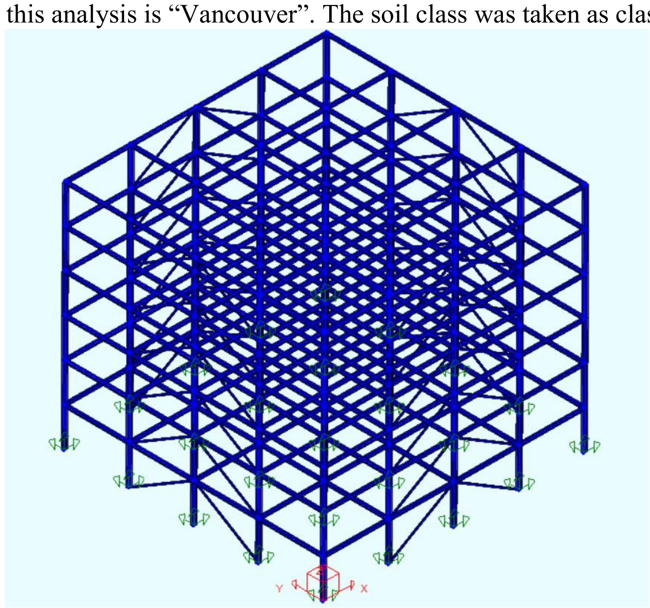

Figure 8: Three-dimensional model of the building

The peak ground acceleration value for Vancouver is 0.47g. The peak spectral acceleration values for this seismic zone is given in Table 1. For this building, both the importance factor and higher mode effect were taken as 1.0. As R_d and R_o are unknown for the PBSC braced frames and it can also be seen from Figure 6 that they exhibit very high ductility (over 10). For this design exercise, a value of 8.0 was considered for R_d and 1.3 for R_o. Besides, designing this braced frame with a low R_d value (4 or below), may not induce nonlinearity in the braces; which will prevent us from assessing the self-centering capability of this bracing system. Furthermore, if this building can resist seismic load and can self-center after designing with a large R_d value (8.0), then the performance of this novel bracing system will be confirmed.

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

After carrying out the analysis and design using CSA S16-2014, it was found out that the required sections for the beams and columns are W250x24 and W310x67, respectively. It was also found out that the minimum required size for the brace for the upper three floors is HS127x4.8. For the 2nd and 3rd floor the required brace section is HS127x6.4 and finally for the ground floor the required size is HS127x8.0.

As nonlinear dynamic time history analysis of three-dimensional building frames are computationally intensive, a two dimensional model was created using the outer perimeter frame. In order to run the analysis only in two dimensions, the following restraint condition was applied to the nodes. All the nodes except the foundation were restraint in U_y, R_z and R_x degrees of freedom. The foundation nodes were restrained in U_x, U_y and U_z directions only. Furthermore, the brace ends were moment released in both local orthogonal planes (M_y and M_z); the torsion was also released in one end. This end release condition prevents bending moment transfer to and from the building frame. The previously mentioned gravity loading (Dead, Snow and Storage) and self-weight of the slab was calculated and applied to the beams as uniformly distributed load as seismic mass. For dead, and self-weight a multiplier of 1.0 was used; whereas, for the snow and storage loads 0.25 and 0.6 were used. The nodal restraint conditions and the gravity loading on the beams are shown Figure 9(a) and the uniformly distributed loading condition is shown in Figure 9(b).

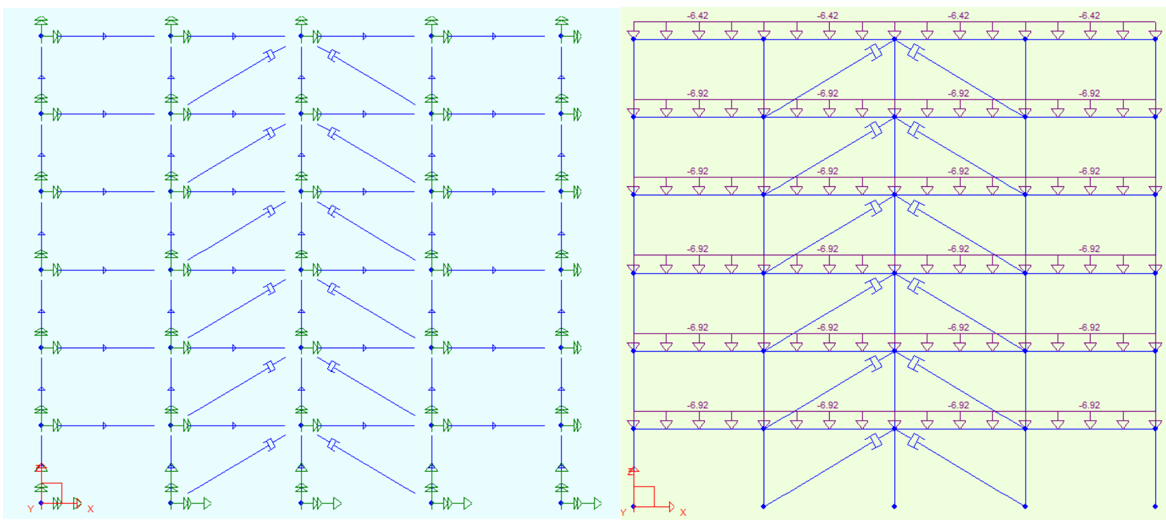

Figure 9: (a) Nodal Restraint Conditions (b) Uniformly distributed gravity loading on the beam for 2D model.

The dashpot shapes shown at the end of the braces represents the zero length link elements. 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 that were used to design the brace sections were retrieved from the 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 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 N/mm^2. The result gave the required 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. Buildings are normally 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 are capable of recovering from 6%-8% strain, we can comfortably make the NiTinol bars of the PBSC brace 1/6th to 1/8th of the total brace length. This will also result in material and cost savings. The above-mentioned parameters were provided as input to the MATLAB quasi-static analyzer developed for the PBSC brace and hysteresis were generated. 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 10 shows the link input parameters used for the HS127x8 brace section.

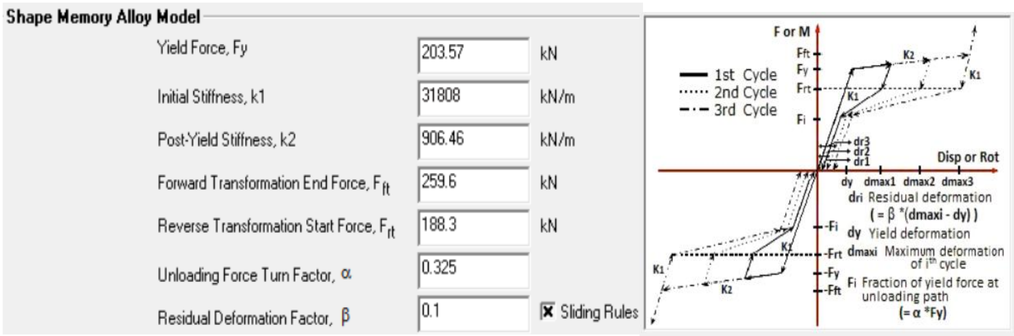

Figure 10: Sample input data for PBSC link hysteresis

8. RESULTS

The above-mentioned frame was analyzed using ten historically significant earthquake records. These records are as follows: Imperial Valley, ChiChi, Corralitos, Emeryville, Trinidad, Kobe, Kocaeli, Loma Prieta, Northridge, Sakaria. These records were matched with Vancouver soil class “C” response spectrum before the analysis. The spectrum matching was done using the SeismoMatch (2015) software, which utilizes the wavelets algorithm developed by Abrahamson (1992), and Hancock et al. (2006).The scaled spectral acceleration vs time period (Sa-T) plot of the matched records are shown in Figure 11.

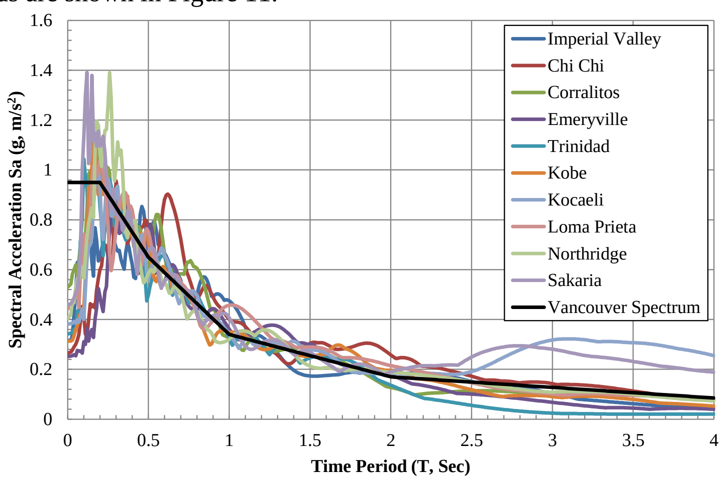

Figure 11: Matched response spectra of the ten earthquake records

After the spectrum matching, these ten earthquake records were used to run the nonlinear dynamic time history analysis on the braced frame. From these analyses results, the following parameters were chosen for investigation: Maximum roof drift %, Residual roof drift %, Maximum interstory drift % and residual interstory drift %. Figure 12 shows the comparison between maximum roof drift % and residual roof drift % for the ten earthquake records.

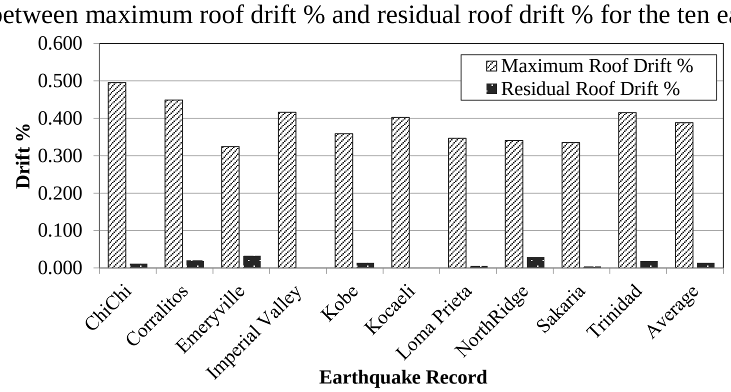

Figure 12: Maximum and Residual Roof Drift Percentage

It can be seen that the maximum roof drift % was 0.49%, which is well below the code specified limit. Furthermore, the maximum “residual roof drift %” was found to be 0.032% for the Kocaeli earthquake record. This value is also extremely low compared to traditional steel buildings. For the 18m tall building frame, this equates to a value of 5.76mm. This low residual roof drift ratio can be attributed to the performance of the self-centering bracing system.

Figure 13(a) and (b) compares the maximum and residual interstory drift ratios for the ten earthquake records. It can be seen that the maximum interstory drift ratios for all ten-earthquake records are very close to one another except the ChiChi record. It can be seen that the maximum interstory drift ratios were observed mostly in the 3m and 12m level, which are 1st and 4th floor of the building respectively.

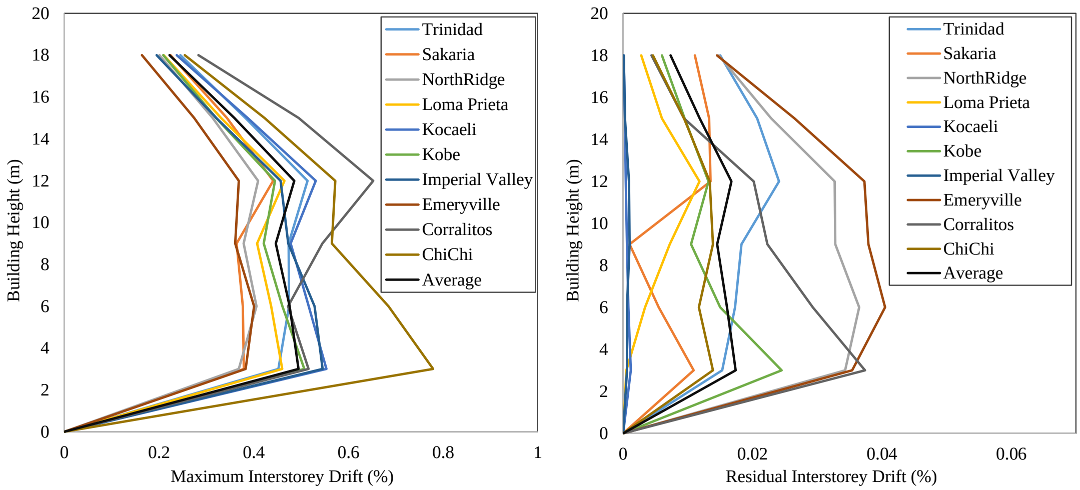

Figure 13: (a) Maximum Interstory Drift Percentage (b) Residual Interstory Drift Percentage

The maximum value is 0.78%, which is around 1/3rd of the code specified limit. Furthermore, the average value was found to be around 0.5% only. On the other hand, the residual interstory drift values were found to vary more significantly between the earthquake records. The range is from 0 to 0.04%, which is a much wider band compared to the maximum interstory drift ratios. Here the maximum values are mostly observed at 3m and 12m level (1st and 4th floor). The average was found to be around .015%.

Figure 14 shows the brace hysteresis for ChiChi earthquake record. Six figures from (a) to (e) represents brace hysteresis from first to sixth floor. It can be observed that the nonlinearity is highest in the first floor and it gradually becomes linear at the sixth floor.

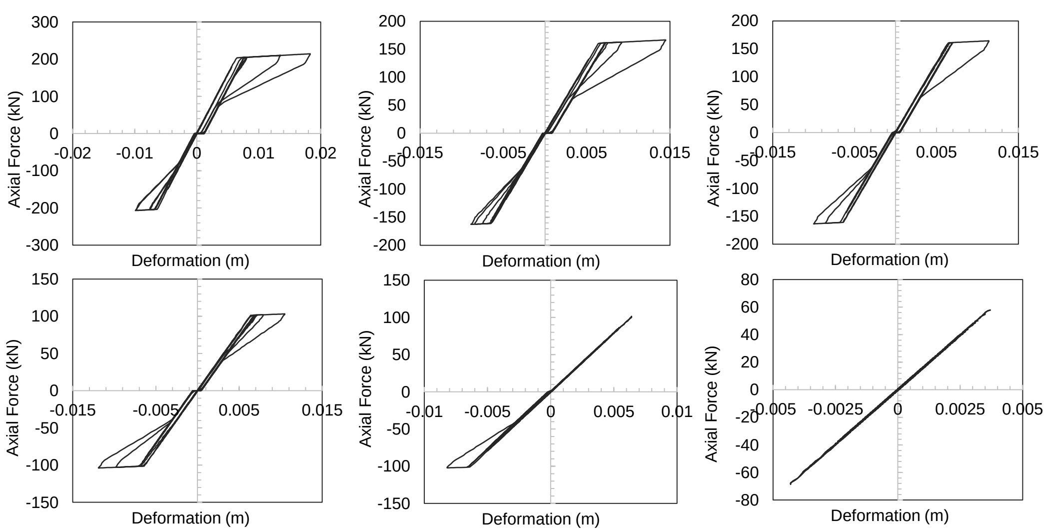

Figure 14: Brace hysteresis for ChiChi earthquake (a) First story (b) Second story (c) Third story (d) Fourth story (e) Fifth story

9. CONCLUSION

A tension only uniaxial superelastic SMA material model has been developed with residual deformation and it was used in a MATLAB finite element program to generate the hysteresis of the PBSC bracing system. The resultant brace hysteresis was found to exhibit sliding behaviour. The brace hysteresis rules were analyzed, an algorithm was developed, and finally it was integrated in the S-FRAME structural analysis and design software's link element. This finite element program was used to run dynamic time history analysis on a braced frame using ten earthquake records matched with Vancouver soil class "C" response spectrum. From the displacement response of the frame it was found out that although the maximum interstory drift ratio reached almost 0.78%, the residual interstory drift was below 0.04%, which is insignificant for a building frame. Furthermore, similar behaviour was observed for maximum roof drift and residual roof drift ratio. Therefore, it can be concluded that the PBSC bracing system is excellent in reducing residual deformation in buildings. Therefore, a structure equipped with this bracing system will be able to self-center after the earthquake is over.

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