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DETAILED COMPONENT MODELLING OF A SELF-CENTERING ENERGY DISSIPATIVE BRACE SYSTEM

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Abstract. *The self-centering energy-dissipative (SCED) brace is a new steel bracing member that provides damping to a structure and a re-centering capability, reducing or eliminating residual building deformations after major seismic events. Recently, the SCED concept has been extended through the design and construction of a new enhanced-elongation telescoping SCED (or T-SCED) brace that allows for self-centering behaviour over a range that is two times as large as the range that could be achieved by the original SCED bracing system. Previous prototype tests of SCED and T-SCED braces have shown that the simplified estimates of the initial brace stiffness that were previously used do not predict the results from the prototype tests well. To accurately model the mechanics of these new systems, a new software tool has been developed that is able to represent the detailed behaviour of SCED braces to determine realistic brace stiffness and the effect of construction tolerances on the brace behaviour. In this paper, the inner workings of the software tool are described and its analysis results are compared to the test results from the two previous experimental studies to demonstrate the software's ability to model SCED and T-SCED behaviour accurately.*

1 INTRODUCTION

The self-centering energy dissipative (SCED) brace is an innovative bracing system for structures that has recently been designed in Canada [1]. The mechanics of the SCED brace system are shown in Figure 1. The inner and outer members in the figure are connected to opposite ends of the brace. Two free end plates, one at either end of the two members, abut the ends of both. Post-tensioned tendons connect the two end plates. These tendons elongate both when the brace is in tension and when it is in compression. This provides a restoring force to the system which causes it to be self-centering. An energy dissipation element is also present. This dissipator may consist of a friction, yielding, viscous or shape memory alloy device and it acts on the basis of the relative movement of the inner and outer sections. The effect of the self-centering behavior combines with the energy dissipation to create the flag-shaped hysteretic response shown in Figure 2.

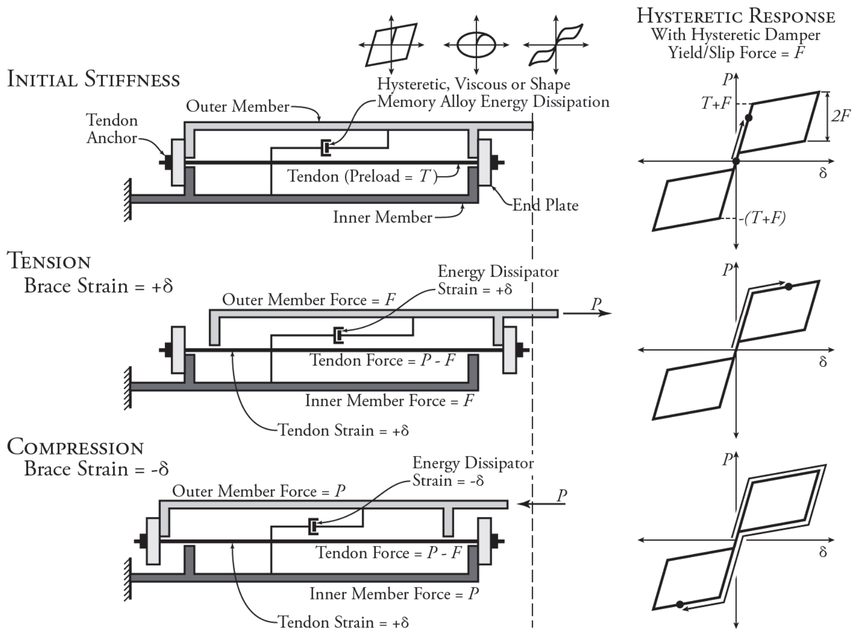

Figure 1: SCED Brace Mechanics (adapted from [1])

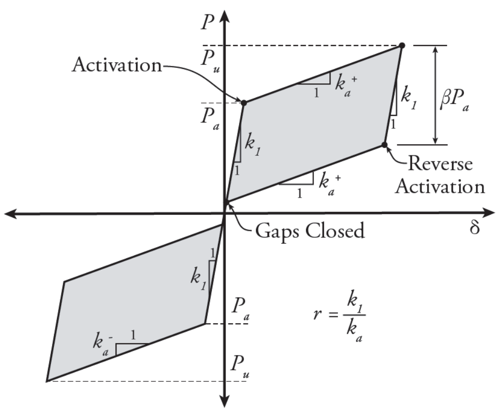

Figure 2: SCED Brace Simplified Hysteresis

The SCED brace concept has recently been extended to achieve double the elongation capacity of the brace for a given type and length of tendons. This concept utilizes one or more intermediate members in between the inner and outer members to allow the use of one or more extra sets of tendons [2]. The extra sets of tendons are effectively in series with the original set, meaning that each set of tendons will share the total deformation of the brace. This new type of SCED brace is called the telescoping SCED or T-SCED and the mechanics of the system are shown in Figure 3.

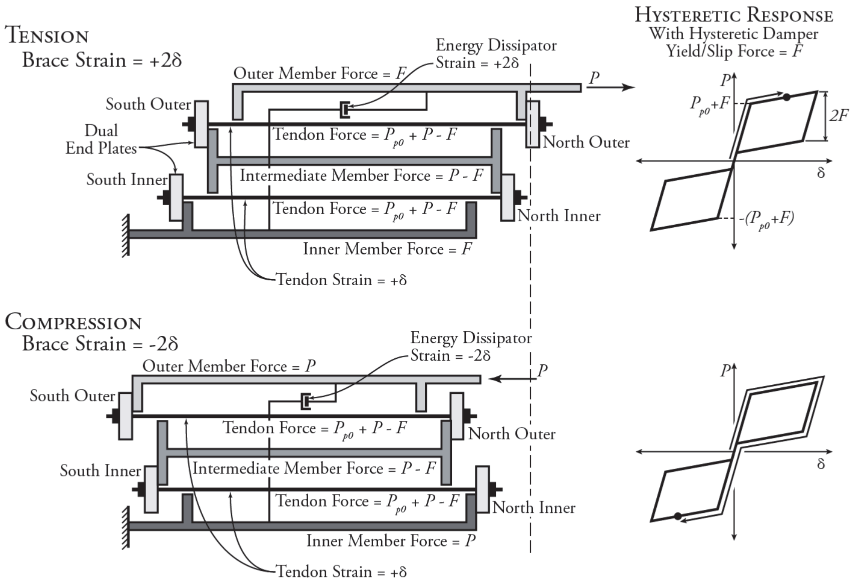

Figure 3: T-SCED Brace Mechanics [2]

Previous tests of SCED and T-SCED braces [1-3] have determined that the initial stiffness of SCED braces as calculated using the simplified method discussed in [1] do not provide a good estimate of the true initial stiffness found during physical testing. It was suspected that this discrepancy may have been caused by imperfect construction tolerances that were applied to the total length of the inner, intermediate and outer members. Since the effect of member length differences on the hysteretic behavior of SCED and T-SCED braces could not practically be developed using a closed-form mechanics solution, a mechanics simulation program was written which uses a nonlinear stiffness method analysis to calculate a more realistic hysteretic behavior. This program is called the SCED Mechanics Simulator and it can simulate the hysteretic effect of any combination of member stiffnesses, arbitrary internal friction damper slip forces at either end of the brace, and member length construction tolerances. It also includes the ability to add viscous damping in parallel with the brace and to simulate the effect of that damping at a specific sinusoidal frequency.

This paper will present the algorithmic implementation of the SCED Mechanics Simulator and the user interface. The Mechanics Simulator will then be used to investigate the effect of construction tolerances on the hysteretic behavior of the brace and the initial stiffness. Then, two previous SCED and T-SCED brace prototype tests will be modeled to show that the simulator provides a good prediction of real brace hysteretic response.

2 THE SCED MECHANICS SIMULATOR MODEL

The SCED Mechanics Simulator requires a web browser in order to run. The program may be found online at "www.erochkoengineering.com/SCED". It was programmed using HTML5 and JavaScript so that it is cross-platform compatible and may be served to users over the web. As such, any computer system with a modern web browser can use the software whether the system is Windows, Mac, or Linux-based. All of the programs inputs, outputs and interactive elements are contained within a single dynamic webpage. The open-source JavaScipt package Sylvester was used to provide linear algebra capabilities for the mechanics calculations [4]. A number of other open-source JavaScript packages were used to facilitate other various user interface capabilities. The package JQuery was used to add dynamic functionality to the HTML page [5]. JQueryUI was used to provide the visual user interface elements for the input forms, buttons and sliders [6]. The JQuery extension Flot was used to provide dynamic data plotting and charts [7]. The dynamic schematic of the SCED brace was drawn using the HTML5 canvas element, but backwards-compatibility support for the canvas element in older browsers was provided using the package ExplorerCanvas [8]. Input box validation to restrict users to appropriate input values and ranges was provided using the LiveValidation javascipt package [9].

2.1 Algorithmic Implementation

The SCED Mechanics Simulator models SCED brace hysteretic behaviour using a nonlinear incremental stiffness method analysis. The stiffness matrix for the analysis contains elements that are connected and arranged as shown in Figure 4. The model itself is effectively one-dimensional; however, for clarity, the figure shows the model elements spaced out in two dimensions. As the figure shows, two different stiffness matrices are possible depending on whether the brace being modelled is an original SCED or a T-SCED. The elements that represent the inner, intermediate and outer members (k_i, k_m, k_o), and the tendons (k_p, k_{p1} and k_{p2}) have a permanent linear stiffness which is dictated by the input parameters. The connection stiffness element (k_{conn}) also has a permanent stiffness dictated by an effective series connection stiffness provided in the inputs. The end plate contact elements ($k_{g[\,]}$) represent the contact between the end surfaces of each of the axial members and the end plates. The stiffness of these contact elements is set at each analysis step to be equal to either the bearing stiffness provided in the inputs (during contact), or a small non-zero stiffness (when not in contact). The internal friction damper elements (k_{f1} and k_{f2}) represent the conditional stiffness of the friction dampers. Similar to the contact elements, at each analysis step the stiffness of each friction damper element is set to the friction interface stiffness provided in the inputs when the damper has not slipped and a small non-zero stiffness when the damper is slipping. For the T-SCED model, the end plate friction elements (k_{ep1} and k_{ep2}) work similarly, changing stiffness based on the friction slip between the inner and outer end plates. These elements simulate the effect of friction between the T-SCED's inner and outer end plates. For each analysis step, the simulator calculates the locations, lengths, axial force, and elongation for every element in the model. The stiffness method analysis was performed using the Payne and Irons method [10].

The first stage of the analysis is to apply the pretensioning to the tendon elements to determine the initial state of the brace prior to external loading. During this stage, it is assumed that the internal friction dampers are not active and, therefore, do not provide any stiffness. The pretensioning force is applied in small force steps. The step increment for this pretensioning force is defined in the software input. The left end of the brace (node 0 in Figure 4) is considered to be restrained. The force increment for each step is applied as a fixed-end force to the tendon elements. For each step in the pretensioning analysis, a new stiffness matrix and fixed end force matrix are created. The resulting forces and displacements in each element after each step are then calculated and recorded. The pretensioning analysis is complete once the total force in the tendons reached the target pretension force.

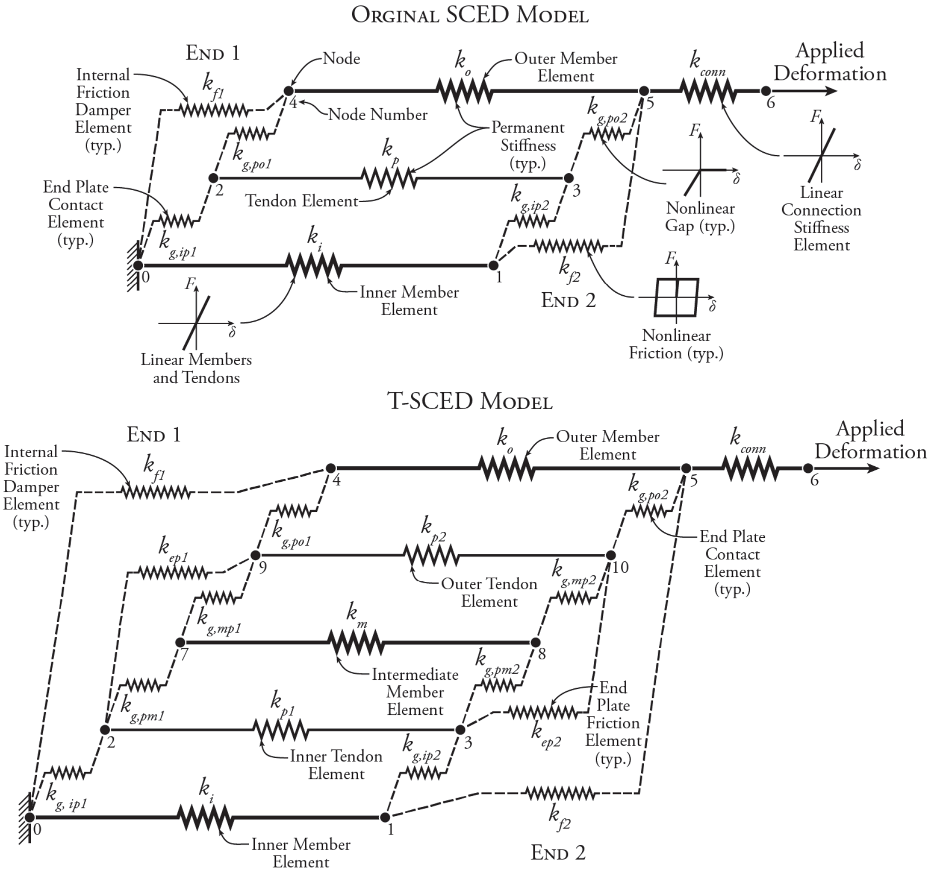

Figure 4: SCED Mechanics Simulator Model.
Note: Both models are one-dimensional, but are shown here separated into two dimensions for clarity

Once the pretension is fully applied, the full brace is deformed in the directions and magnitudes specified in the program input. During this single cycle analysis, node 0 is restrained and the axial deformation of the brace is controlled by applying incremental displacements to the free end of the brace (node 6 in Figure 4). The deformation step increment is defined in the software input. For each step in the hysteretic analysis, a new stiffness matrix and fixed and force matrix are constructed that take into account the locations of the end plates at either end of the brace and the conditional stiffness of the friction damper elements. An end plate contact element is located between the ends of the tendons and the end of each axial member. These end plate contact elements are given a very large or very small stiffness depending on whether the location of the axial member coincides with the end of the tendon or not. If the force in a friction damper exceeds the friction damper slip force, then the stiffness of that element is set to zero, otherwise the friction damper element is given the damper stiffness provided in the input. If viscous damping is specified in the input, the total viscous force for the current step is calculated using the sinusoidal deformation frequency and maximum SCED brace deformation amplitude defined in the input. The hysteretic analysis is complete once the brace has deformed in both directions up to the maximum specified deformation amplitude and then has returned to zero deformation.

The analysis does not cap the forces in any of the elements, including the friction damper and contact elements. Therefore, it is prone to overshoot force and deformation values if the deformation step increment is too large. A small deformation step increment value is necessary to attain high-quality hysteretic behavior simulation results. This step size will typically be on the order of 0.001 mm to 0.05 mm.

2.2 User Interface

The input form for the SCED Mechanics Simulator begins with inputs for the Young's modulus for the steel sections and the pretensioned tendons. This is followed by inputs for the geometry of each steel member. Input parameters describing the geometry of the inner and outer members are always required, and the 'Middle' member which represents the T-SCED intermediate member is optional. By inputting different initial section lengths for each member, the Mechanics Simulator can simulate the effect of member length tolerances on the behaviour of the brace. The friction inputs specify the slip force for the internal friction dampers at each end of the brace. These may be different from each other and may be set to zero to eliminate internal friction damping. Tendon inputs are provided for the cross-sectional area of the tendons and the tension pretension during brace assembly. Viscous damping inputs are optional. The viscous damping that is specified by the input damping constant adds a force to the model at each step that depends on the specified cycle frequency and the analysis deformation limits. A last set of model inputs allows the user to model a connections in series with the brace.

The user also provides inputs which determine how the analysis is conducted. The first analysis input allows the user to specify the bearing stiffness and friction interface stiffness. The default stiffness values (100000 kN/mm for both) tend to provide the most stable analytical results for most practical design cases. The next inputs specify the force step that is used for applying the tendon pretension as described in the previous section. The deformation step input determines the size of the deformation steps for the hysteretic analysis that follows the pretension analysis. The last two analysis inputs determine the maximum deformations that are applied to the brace model in each direction.

After the 'Calculate SCED' button is pressed, the pretensioning and hysteretic behaviour calculations are performed and the results of the analyses are presented as shown in Figure 5. The top two plots depict the pretension load in each of the members. The left plot shows the axial force in each member as a function of the load step, which shows when each member begins to take tendon pretension force. The right plot shows the axial force in each member as a function of each member's axial deformation. This plot represents the hysteretic behaviour of each member during tendon pretensioning.

Below the pretensioning analysis plots, there is a dynamic schematic showing the forces and deformations of each element of the SCED brace. This schematic is similar in form to the brace schematics shown previously in Figures 1 and 3. The horizontal slider that is below the schematic allows the user to select an analysis step. The state of the brace for the selected step is then shown in the schematic. Text input boxes above and below the slider allow the user to select a step by the step number and to change the horizontal scale of the dynamic schematic so that deformations may be exaggerated. The coloured rectangles immediately below the schematic represent the force present in the internal friction dampers. Both pretension analysis steps and hysteretic behaviour analysis steps may be shown by the dynamic brace schematic.

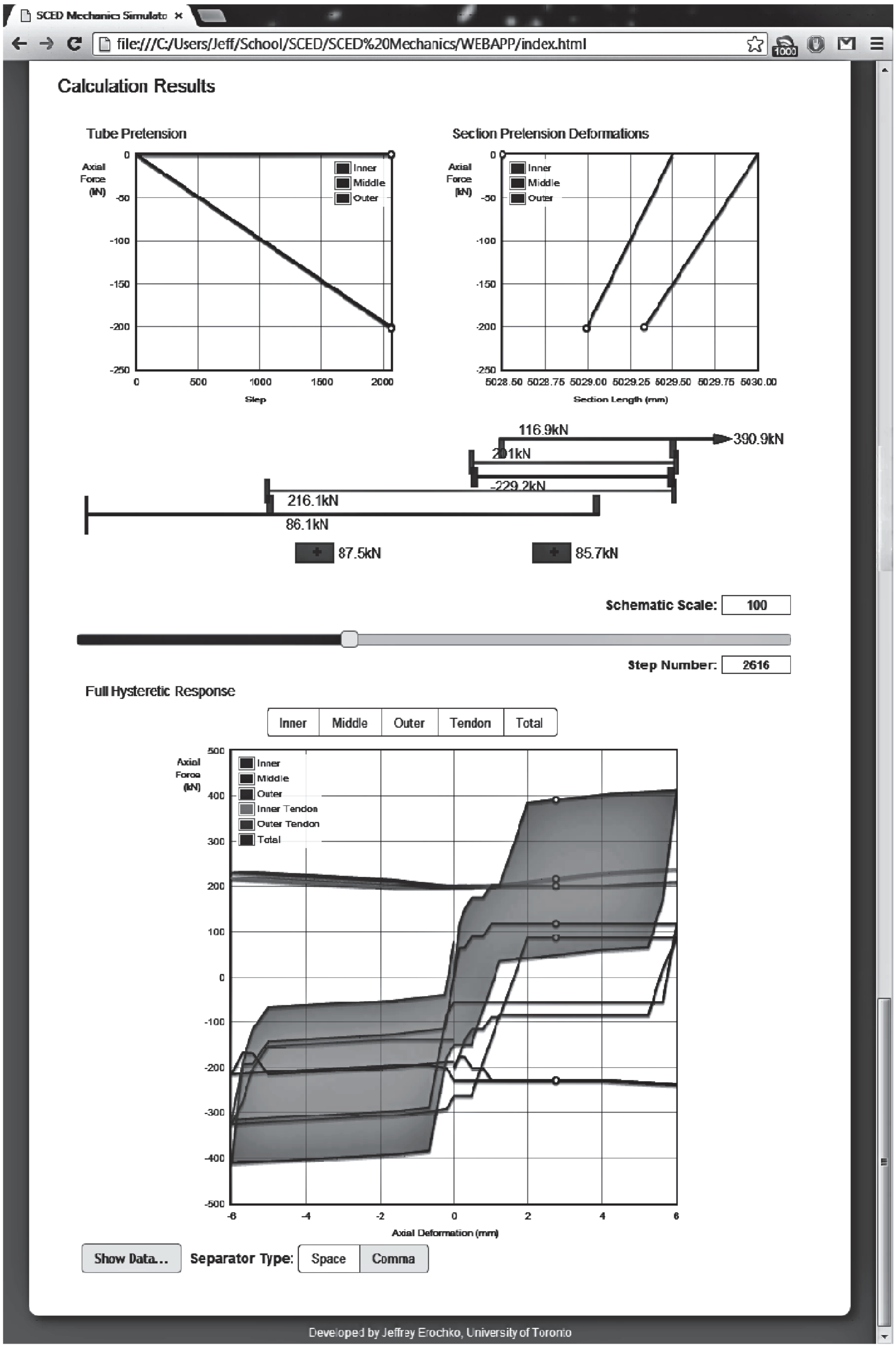

Figure 5: SCED Mechanics Simulator Results

The large bottom plot in the results output shows the total hysteretic behaviour of the SCED brace as well as the hysteretic behaviour of the individual brace elements (the axial members and the tendons). For the individual elements, the hysteretic behaviour is plotted as the force in that element versus the total deformation of the brace. For each hysteresis shown in that plot, a circular marker identifies the point on the hysteresis that is represented by the step selected by the slider above and the state shown by the dynamic schematic above that.

After the calculation is complete, the full result data set may be output in a text format for further post-processing.

3 VALIDATION OF THE SCED MECHANICS SIMULATOR

For some relatively simple SCED brace design scenarios, closed form solutions have been previously derived for the hysteretic behavior [11]. To validate the SCED Mechanics Simulator, one of these example scenarios was simulated using this tool. A comparison of these two analyses is shown in Figure 6. As the figure shows, both the full step-wise calculations and the simulated response produce identical hystereses. Since there are no practical closed-form solutions for the T-SCED detailed mechanics or for the effect of member length tolerance, there is no way to perform a theoretical comparison for those scenarios; however, real experimental test results will be used to validate the predictions from the SCED Mechanics Simulator to assess its performance when used to model those types of scenarios.

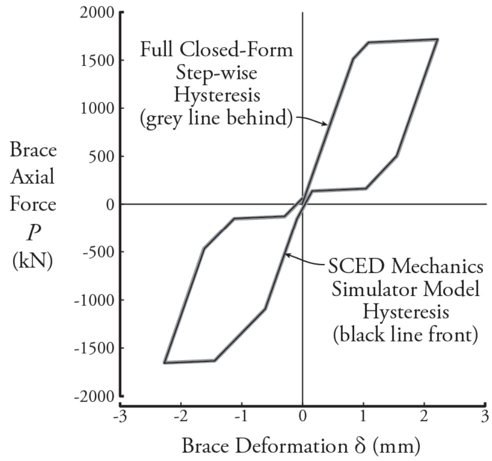

Figure 6: Detailed Mechanics Results vs. Mechanics Simulator Model for a Sample SCED Brace

4 THE EFFECT OF FABRICATION LENGTH TOLERANCES

As mentioned previously, in a real SCED brace, the length of the inner, intermediate and outer members of the brace will not be exactly identical. The axial members will have a construction tolerance that applies to their length. In practice, the manufacturer of the brace may be asked to use any length tolerance to within a fraction of a millimeter; however, tighter tolerances are associated with higher costs, especially for elements that are the size and length of typical SCED brace elements. Since the SCED Mechanics Simulator can effectively simulate the effect of different construction tolerances, it is possible to attain a better understanding of the effect of construction length tolerances on the behaviour of SCED and T-SCED braces. This will help a designer of SCED braces to determine what tolerance is appropriate.

The same sample SCED brace that was used in Figure 6 is used to study the effect of differing axial element lengths as shown in Figure 7. The figure shows a comparison of the low amplitude hysteretic response of the brace under different member length scenarios. These hystereses are only shown for a deformation amplitude of +/- 2.25mm so that the different transitional stiffnesses are clearly visible.

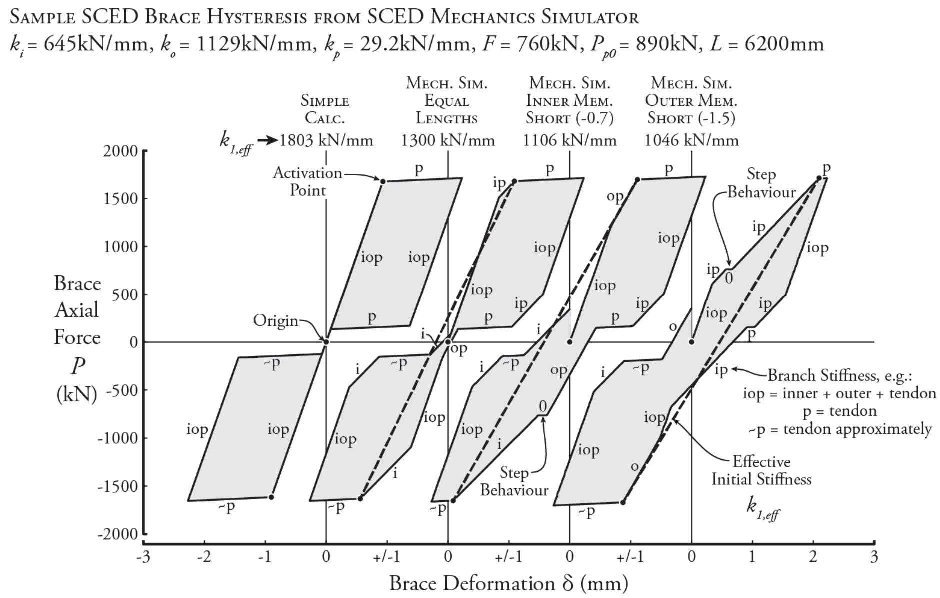

Figure 7: Sample SCED Brace Hystereses - Effect of Length Tolerance

The left hysteresis in the plot represents the idealized simplified behaviour of the brace with a simple initial stiffness equal to the sum of all three axial elements and a post-activation stiffness equal to the stiffness of the tendon. This is the brace behaviour that would be predicted by the simplified design equations [1]. To the right of that simplified hysteresis is the realistic hysteresis of a SCED brace in which the inner and outer members have different stiffnesses but identical lengths. As this plot shows, the initial stiffness before activation for a perfectly constructed brace is multilinear.

The two hystereses on the right of the plot show the effect of different inner and outer member lengths due to construction tolerances. The third hysteresis from the left shows the behaviour of the brace if the inner member is 0.7mm shorter than the outer member and the fourth hysteresis shows the behaviour if the outer member is 1.5mm shorter than the inner member. These values were chosen such that both members still take some load during pretensioning, but most of the load is taken by the longer member.

These two hystereses show that the behaviour of the brace becomes significantly more complicated when the lengths are not equal. The initial stiffness branches of these hystereses do not show a consistent pattern with respect to the different element stiffnesses. In addition, there are some portions of the hysteresis that have zero stiffness, causing ‘steps’ in the response. This step behaviour becomes much more pronounced as the difference between the member lengths becomes greater.

The most significant effect caused by the member length differences is the impact on the effective initial stiffness of the brace. This effective stiffness may be defined as the slope between the positive and negative activation points. The effective stiffnesses of the different brace scenarios are shown above each plot in Figure 7. As the stiffness values show, the effect is significant: even for the SCED with identical length members, the realistic effective initial stiffness of the brace is almost 30% lower than the value that would have been predicted by the simplified equations. With the modest construction tolerances provided in the two right-most hysteresis in Figure 7, the initial stiffness may drop by another 10% to 15%. For T-SCED braces, the effect is even greater since they have three axial elements; the effective initial stiffness can be as low as 20% of the assumed simplified value. It is clear that, especially for force-based designs, it is critical that designers use the more realistic values for the effective initial stiffness.

5 COMPARISON OF SIMULATOR MODEL RESULTS WITH TEST DATA

To demonstrate the hysteretic response predictions that may be attained using the SCED Mechanics Simulator, two examples will be presented below. The first is a small-scale conventional SCED brace with construction tolerance issues and the second is a full scale T-SCED brace prototype.

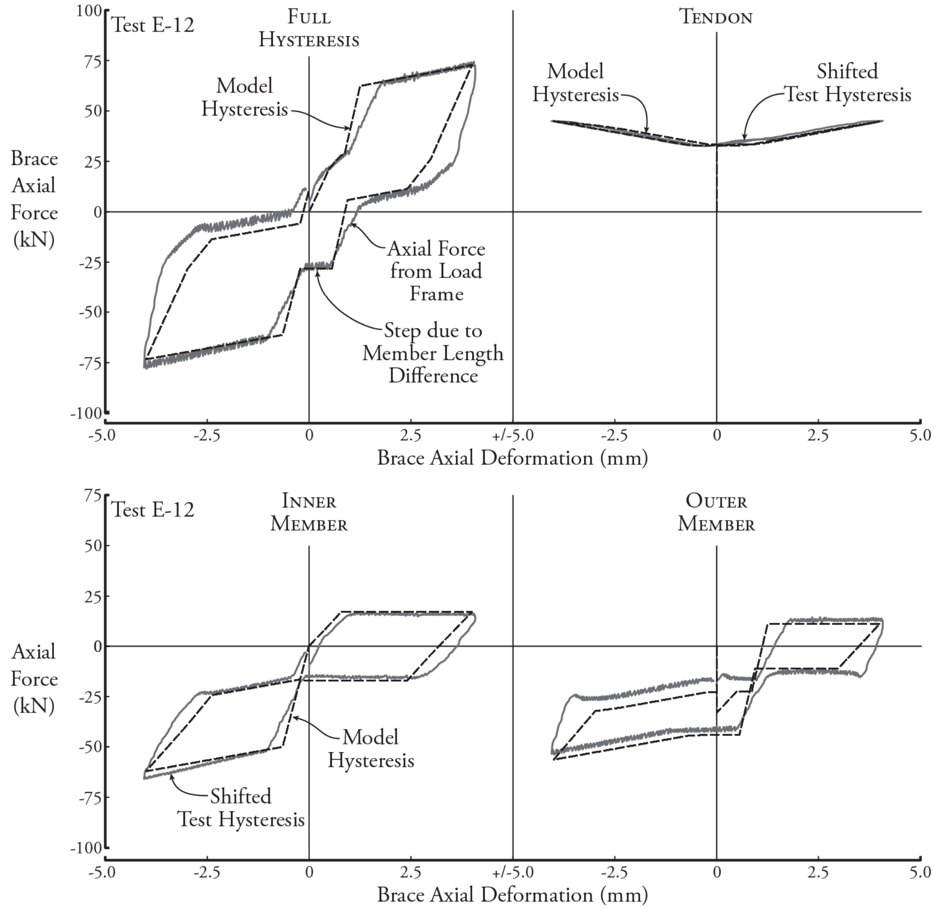

Figure 8: Small-Scale SCED Brace Hysteretic Response Modelled using the SCED Mechanics Simulator

5.1 Small-Scale SCED Brace

The shake table tests of a SCED-braced frame that were previously conducted used small-scale SCED braces [3]. One of these braces had a construction length tolerance problem when it arrived whereby the inner and outer member lengths differed by up to 1mm [11]. This represents a challenging modelling scenario for the SCED Mechanics Simulator because this brace exhibited the step behaviour caused by unequal member lengths as previously identified in Figure 7. This brace also had unequal internal damper friction slip force at each end. A comparison between the model response and a small amplitude test hysteresis is shown in Figure 8. In the figure, the measured test hystereses were vertically shifted to account for the fact that the measured values do not include the effect of the initial tendon pretension.

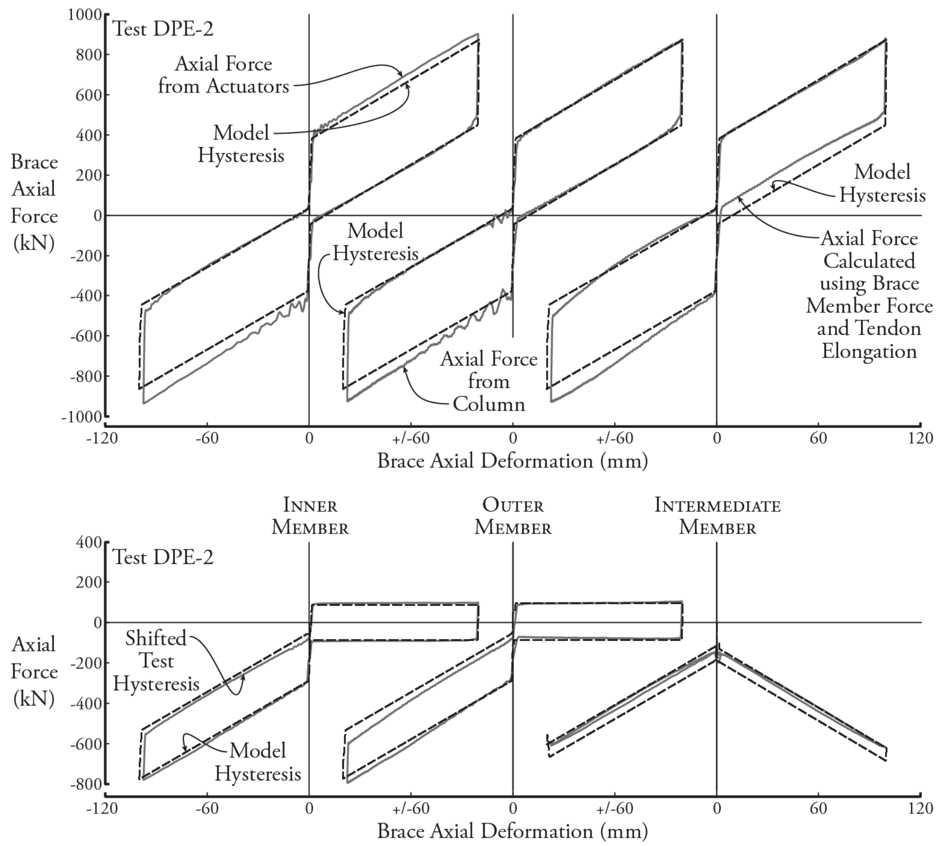

Figure 9: T-SCED Brace Hysteretic Response Modelled using the SCED Mechanics Simulator

This model included a flexible friction interface with a stiffness of 30kN/mm. The tendon pretension force and the damper friction were calculated based on the hysteretic response of the test brace. The division of the internal friction damper force between the two ends was determined based on the relative widths of the inner and outer member hystereses. The member lengths were selected such that they provided a good fit for the test hysteresis data. As the figure shows, using these parameters the SCED Mechanics Simulator model provided a good approximation of the response of the real system, including the step behaviour and the hysteretic response of the individual brace elements.

5.2 Full-Scale T-SCED Brace

A full-scale prototype T-SCED brace has previously been constructed and tested [2]. Figure 9 compares the detailed large-cycle response of the real T-SCED brace to the simulated response of the brace using the SCED Brace Mechanics Simulator. This T-SCED brace was tested within a full scale steel portal frame [2]. The material properties, element areas, and connection geometry were determined using known brace properties. The tendon pretension and friction forces were calibrated through comparison to the measured element and brace hystereses.

The top axis in Figure 9 shows the overall hysteretic response of the brace. The left hysteresis compares the brace axial load calculated using the actuator force to the simulated response. It shows that this calculation overestimates the response due to the inclusion of friction in the frame and between the frame and the lateral supports. The middle hysteresis uses the brace axial load that was calculated using the projected axial load from the south column of the portal frame. This data shows a vibration in the force response due to the slip and impact of the test portal frame beam connection to the column. Despite these local effects, this response gives the best overall characterization of the envelope of the hysteretic response of the brace. It also compares well to the predicted hysteresis determined using the Mechanics Simulator model. The right hysteresis uses the axial force as calculated from the brace instruments (LVDTs measuring the end plate movements and strain gauges on the inner, intermediate and outer members). This hysteresis does not agree well with the model hysteresis; it under-predicts the width of the flag hysteresis on the tension side and over-predicts the width on the compression side. This effect was caused by friction induced by the rubbing together of the inner and outer end plates at each end. This changes the values of the parameters for the axial force calculation; however, as the hysteresis derived from the axial force in the column shows, this calculation error does not affect the true hysteretic behaviour of the brace. The effect of this end plate friction was included in the Mechanics Simulator model to accurately predict the hystereses of the inner, intermediate and outer members.

The measured effective initial stiffness of the brace that was calculated by finding the secant stiffness between the tension and compression activation points and was approximately equal to 285 kN/mm. The Mechanics Simulator model predicted a value of 340 kN/mm with a member length difference of 0.7mm between the inner and intermediate members and 0.3mm between the intermediate and outer members; this value is reasonably close to the measured effective initial stiffness. These effective initial stiffnesses are much lower than the theoretical initial stiffness for this brace which is 1476 kN/mm. Since this T-SCED brace was fabricated carefully to ensure that the members were the same length, it is unlikely that better fabrication practices could be followed during mass production. Therefore, it is clearly important that a designer considers a realistic effective initial stiffness estimate for the determination of earthquake loads and for drift calculations.

6 CONCLUSIONS

- A newly created software tool called the SCED Mechanics Simulator has been created to model the detailed hysteretic behavior of SCED and T-SCED braces. This software tool is able to consider the effect of axial member length tolerances which significantly affect the effective elastic stiffness properties of SCED and T-SCED braces.
- Use of the software has shown that the initial stiffness of SCED and T-SCED braces is not adequately represented by the simplified design equations. Realistic effective initial stiffness may be as low as 60% of the simplified values for SCED braces and as low as 20% of the simplified values for T-SCED braces.
- Therefore, it is critical that designers use a tool such as the SCED Mechanics Simulator to determine realistic effective initial stiffness values of SCED and T-SCED braces during the design process.
- The SCED Mechanics Simulator provides good predictions of the hysteretic behavior of real SCED and T-SCED brace prototypes.

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