Ultra-Low Cycle Fatigue Behaviour of Steel Concentrically Braced Frames Under Extreme Seismic Loads

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Abstract

Steel concentrically braced frames (CBF) are commonly used in the current construction industry due to its ability to dissipate input seismic energy effectively during extreme earthquake loadings as a result of global buckling phenomena of braces deliberately designed to buckle in compression. Even though this global buckling is favorable to CBF, local buckling in the middle of the braces due to high strain concentrations imposed by the cyclic action leads the braces to failure sooner than expected. This phenomenon occurs because of the crack initiation at the vicinity of amplified strains which can be described by the ultra-low cycle fatigue failure. Various methods (i.e. Cyclic void growth model (CVGM), stress modified critical strain model etc.) have been proposed by researchers to tackle this fracture initiation where those methods require a detailed finite element model followed by a complete history of stress and strain variation over the loading until the fracture. This sort of a finite element model seems impossible when it comes to a multi-storey CBF system as it demands a high computational cost. To overcome this, braces were modeled using nonlinear fiber beam-column elements offered in software such as OpenSees in which the structural behavior of the braces can be easily and accurately taken. However, resultant stress-strain histories cannot be implemented directly in CVGM as those are very low and inaccurate because of the small displacement theories used in the fiber element formation. This study proposes a new simplified CVGM which can be used in supporting the OpenSees framework. 50 CBF was modeled and hysteretic responses were validated using the literature. Modified damageability values that come under CVGM were iteratively calculated until the failure criterion is satisfied. Multiple regression was used to formulate the new simplified CVGM as a function of brace properties.

1. Introduction

Catastrophic earthquakes such as 1994 Northridge and 1995 Kobe marked huge unforeseeable devastation to the steel structures. Those damages were inclusive of human lives, money as well as resources. In that time, steel moment resisting frames (SMRF) was very prevalent and engineers asserted that these MRFs can withstand against plastic rotations of 2% or more without failure. However, the above failures exemplified that the performance of these structures should be improved, and subsequently, guidelines were emerged to evaluate the seismic performance of already existing structures and the new structures (FEMA,2000). Following the modifications and developments, concentrically braced steel frames showed a significant increase in applications due to its effective nature during the high seismic events. Researchers found that during high seismic levels, columns, beams, and concentric braces alone cannot perform well without proper structural detailing as well. However, in concentrically braced frames that are deliberately designed and detailed to buckle out of a plane to dissipate incoming seismic energy are commonly subjected to local buckling motivated by the stress concentrations in the middle of the brace if proper detailing and steel sections are not used. This rises with the phenomenon ultra-low cycle fatigue where the braces fail during very few numbers of cycles during a large earthquake.

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In earlier decades, a large number of experimental studies were carried out to predict and identify this failure. As a result, various equations were developed in terms of brace geometry by various researchers. However, the reliability and accuracy were questionable due to the large empiricism of the formulations and lack of studies to extrude proper conclusions. Following that, later, strain-based approaches emerged and the failure was predicted by the stress and strain histories given from a detailed finite element model. The cyclic void growth model (CVGM) developed by Kanvinde et al., (2007) is one such sophisticated formulation to predict the ultra-low cycle fatigue failure of steel structures. It is important to note that this method requires a strain and stress history under a given loading, generated by a detailed 3D finite element model. Even though analyzing a numerical model of sub-components or assemblages using current finite element packages (i.e., ABAQUS, MIDAS, ANSYS, etc.) is very common, it is very rigorous when it comes to analyzing a multi-story building using these packages due to the high demands of computational power. In this study, the fiber beam-column element (Spacone et al.,1996) utilized within this OpenSees framework was used to analyze the braces which save huge computational time. However, when the results were compared with the continuum finite element model, (MIDAS FEA) it was very clear that the global behavior is accurately predicted but not the local behavior. Therefore, it limits the application of CVGM when the fiber beam-column elements are used because the local behavior basically shows the strain variation which the fiber element does not predict accurately. Therefore, a simplified new cyclic void growth model was proposed in the current study to use within the fiber beam-column element analysis.

2. Methodology

Firstly, the limitations in using the fiber beam-column element in the current research to predict the ultra-low cycle fracture were identified. Then, a set of experiments were validated for force vs displacement response in order to make sure the fiber element predicts the global structural behavior accurately. Resultant, stress vs strain histories for the validated models were used in the formulation of the modified cyclic void growth model which will be discussed in the next sections.

2.1 Identifying the Limitations of Fiber Beam-Column Element

The force-based fiber beam-column element used within the OpenSees framework has the ability to cater moment and axial force interaction as it considers the interaction along the brace by integrating the uniaxial hysteretic material model over the cross-section of the brace. Manegotto-Pinto steel hysteretic model was used in the material model as it considers both kinematic and isotropic hardening together with the Bauschinger effects (Uriz et al.,2008). An experimental study carried out by Shaback (2001) is shown as the demonstration to compare the results between continuum finite element models (MIDAS FEA) modeled by shell elements and inelastic fiber beam-column elements (OpenSees). The specimen (1B) was a tubular hollow steel brace having a width and height of 127 mm and a thickness of 8 mm. Yield stress and Young's modulus were taken as 421 MPa and 191GPa. The brace is fixed at the ends. The cyclic displacement was applied at the ends where gusset plates are connected. Fig.1 illustrates the braced model implemented in OpenSees with two elastic elements, a camber of 0.5%, and five integration points for each element. Please note that gusset plates are connected with two inelastic elements as well. Fig.2 shows the equivalent 3-dimensional shell model having a mesh size of 12.5 mm x12.5 mm.

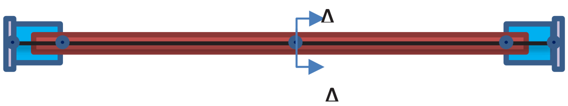

Figure 1: Brace model with two inelastic elements

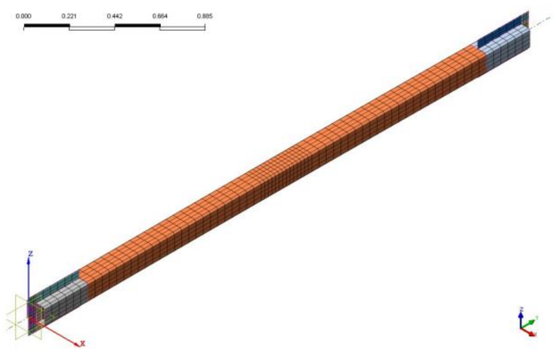

Figure 2: Three-dimensional shell model developed in MIDAS FEA

A cyclic displacement history was applied at the end of the braces as shown in Fig. 3 and observed the global response and the local response. In terms of the global response, axial force vs axial displacement and axial force vs lateral displacement were observed as shown in Fig. 4 and Fig. 5 respectively.

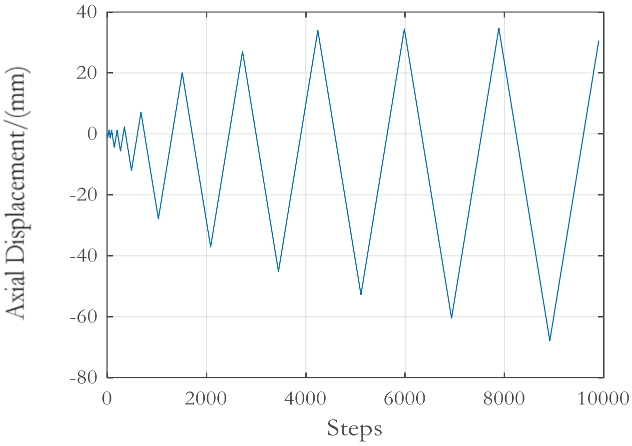

Figure 3: Cyclic displacement history

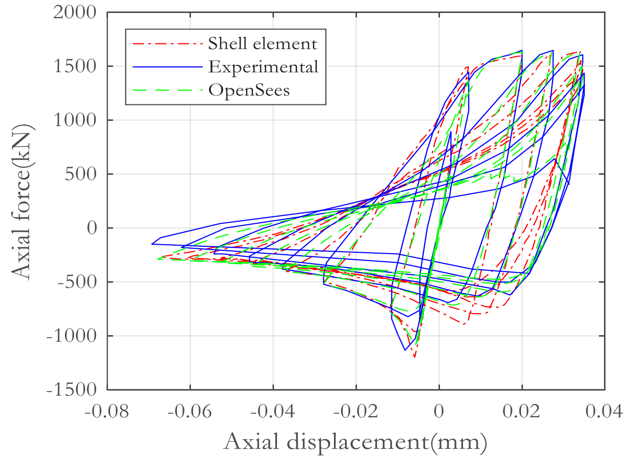

Figure 4: Axial force vs axial displacement variation of shell and fibre models.

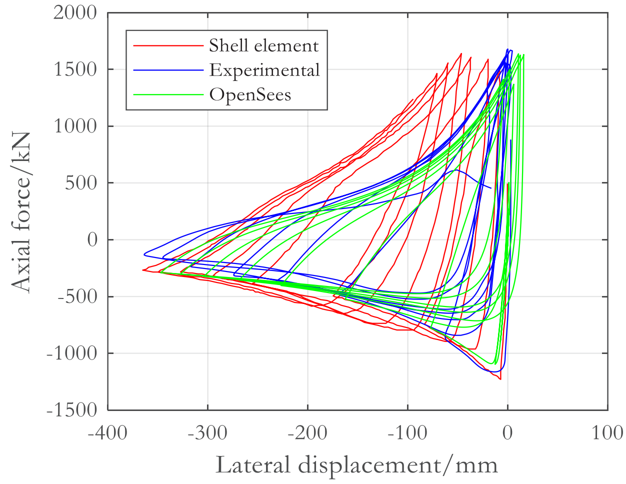

Figure 5: Axial force vs lateral displacement variation of shell and fiber models.

It is clear that the global response of the bracing element can be accurately predicted by both models. It is evident that post-buckling phenomena also can be finely estimated up to a reasonable level by both the models. Figures 6 and 7 delineate the local structural response in terms of strain vs displacement and axial force vs strain respectively.

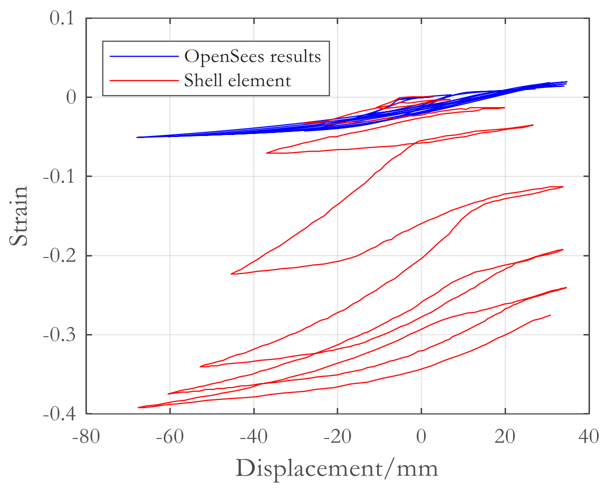

Figure 6: Strain vs Displacement comparison

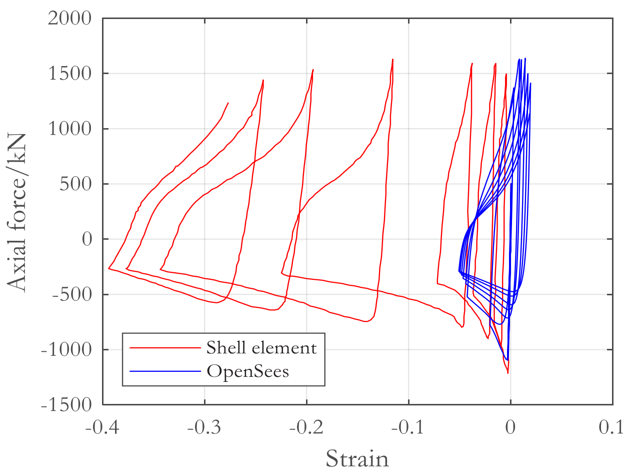

Figure 7: Strain vs axial force comparison

It is very clear from the above graphs that the fiber beam-column element lacks the ability to predict the local structural response where the maximum strain corresponds to the fiber element is about 8 times lesser when compared to that of the shell element. This issue is due to the fiber beam-column elements' inability to predict local buckling phenomena followed by the strain concentrations in the middle of the brace. In contrast, the fiber beam-column element model showed a huge reduction in computational cost compared to the shell model. However, the cyclic void growth model proposed by Kanvinde et al., (2006) requires a full history of stress and strain to calculate the fracture initiation. Therefore, it is very clear that these inaccurate stress and strain histories inferred from the fiber beam-column element cannot be directly implemented in the above cyclic void growth model. Hence, CVGM should be modified.

2.2 Modified Cyclic Void Growth Model

The CVGM equation (Eqn.1) proposed by Kanvinde and Deierlein (2007) is based on the assumption that ductile crack initiation is resulted by the void nucleation, growth, and coalescence followed by the combined effects of plastic stress and strain.

$$VGI_{cyclic} = \frac{\ln\left(\frac{R}{R_0}\right)_{cyclic}}{C} = \sum_{\substack{Tensile\\Cycles}} \int_{\varepsilon_1}^{\varepsilon_2} exp(|1.5T|)\,.\,d\varepsilon_t^p - \sum_{\substack{Compressive\\Cycles}} \int_{\varepsilon_1}^{\varepsilon_2} exp(|1.5T|)\,.\,d\varepsilon_c^p \qquad \text{......(1)}$$

where $R, R_0, C, T, \varepsilon_t^p, \varepsilon_c^p, \varepsilon_1, \varepsilon_2$ and VGI_{cyclic} are void radius at a particular state, initial void radius, constant equal to 1, stress triaxiality, plastic strain in tension, plastic strain in compression, initial strain value, next strain value at a particular strain state, and finally the void growth index (void demand) respectively.

In this model, the failure criterion is given by Eqn.2, where the failure is expected when the void demand exceeds its voids capacity. This void capacity is denoted as the $VGI_{cyclic}^{critical}$ where it represents the maximum number of voids the certain material can withstand without failure. This parameter can be found by Eqn.3 as given below.

$$VGI_{cyclic} \geq VGI_{cyclic}^{critical} \qquad \text{....(2)}$$

$$VGI_{cyclic}^{critical} = VGI_{monotonic}^{critical} \exp\left(-\lambda \varepsilon_p^{accumulated}\right) \qquad \text{....(3)}$$

Here, $VGI_{monotonic}^{critical}$ is the void capacity under monotonic loading that can be calculated using Eqn. 4 together with a notched bar test and an equivalent detailed finite element model. λ is the damageability index in which the effects of stress and stress alteration and material damage are governed in a particular material. $\varepsilon_p^{accumulated}$ stands for the accumulated plastic strain at the start of every tensile excursion.

$$VGI_{monotonic}^{critical} = exp(1.5T)\left(\varepsilon_p^{monotonic}\right)_{critical} \qquad \text{...(4)}$$

In the present study, λ holds a special concern as it is the major parameter that is going to be modified in the modified CVGM.

Moving to the modified CVGM, it is important to note that the stress triaxiality T is replaced by the normalized stress T' (σ_{11}/σ_y) defined for the uniaxial stress state and damageability index (λ) is replaced by a modified damageability index (λ'). Here, σ_{11} and σ_y refer to uniaxial stress and yield strength. Similarly, modified void growth index VGI'_{cyclic} can be written as given in Eqn. 5. Modified critical void growth index $VGI'^{critical}_{cyclic}$ can be calculated using Eqn. 6 where the modified damageability index is included. The calibration of this modified damageability index is discussed in the next section. Likewise, in the previous CVGM, the fracture criterion can be given as in Eqn. 7. Terms, $\varepsilon_t^p, \varepsilon_c^p, \varepsilon_1, \varepsilon_2, \varepsilon_p^{accumulated}$ were taken as the plastic strains generated by the fibre beam-column element brace model but with the same definition mentioned before.

$$VGI'_{cyclic} = \frac{\ln\left(\frac{R}{R_0}\right)_{cyclic}}{C} = \sum_{\substack{Tensile\\Cycles}} \int_{\varepsilon_1}^{\varepsilon_2} exp(|1.5T'|)\,.\,d\varepsilon_t^p - \sum_{\substack{Compressive\\Cycles}} \int_{\varepsilon_1}^{\varepsilon_2} exp(|1.5T'|)\,.\,d\varepsilon_c^p \qquad ....(5)$$

$$VGI'^{critical}_{cyclic} = VGI^{critical}_{monotonic}\exp\left(-\lambda'\,.\,\varepsilon_p^{accumulated}\right) \qquad ....(6)$$

$$VGI'_{cyclic} \geq VGI'^{critical}_{cyclic} \qquad ....(7)$$

2.3 Modified Damageability Index

It is important to note that if the existing damageability index values λ are used in the proposed modified CVGM, failure prediction can not be achieved accurately. Therefore, a modified damageability index value λ' is calibrated such that λ value is iteratively changed until a known fracture is satisfied through the modified CVGM. To exemplify this, an experimental study performed by Shaback (2001) is illustrated below. The hollow square brace specimen (4A) was cyclically loaded until the fracture occurs in OpenSees exactly at the fracture level that occurred in the experiment. Fig. 8 shows the validated force vs displacement global behavior of the model. Then, the resultant maximum stress and strain histories in the middle of the brace were used in the modified CVGM to check the fracture criteria.

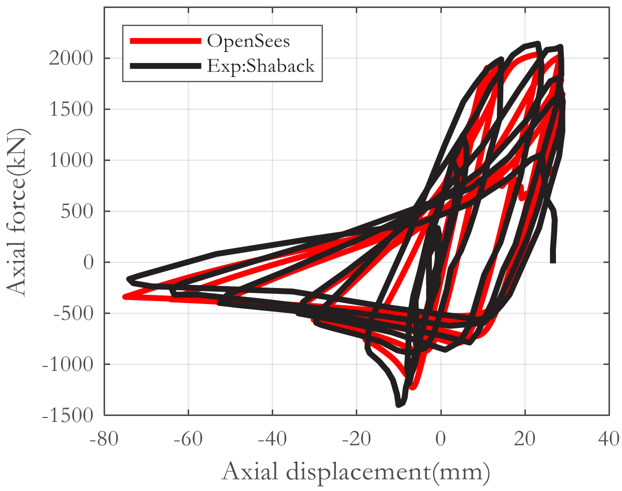

Figure 8: Force vs displacement response of specimen 4A

Figs. 9 and 10 illustrate the failure criterion according to the modified CVGM. Firstly, modified damageability index λ' was assumed as 0.008 and it is clear as shown in Figure 8, the failure criterion is not satisfied. Then, λ' was assumed as 0.016 and Figure 9 shows that the failure criterion is satisfied.

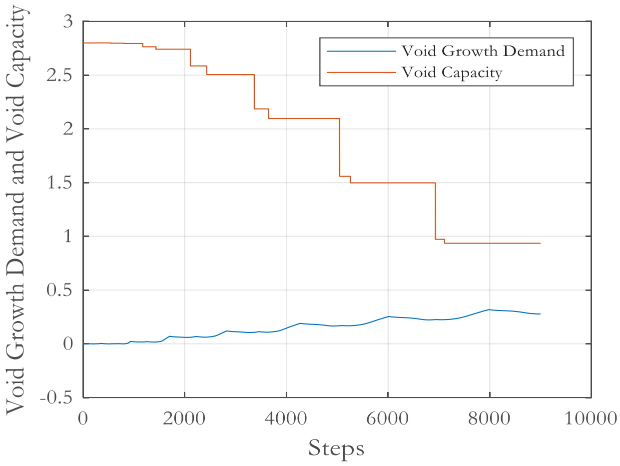

Figure 9: Failure criterion is not satisfied for λ'=0.008

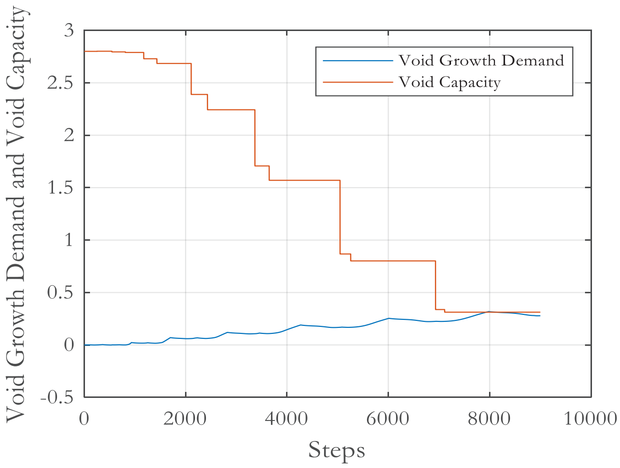

Figure 10: Failure criterion is satisfied for λ'=0.016

Similarly, this procedure was repeated for 50 models and different λ' values were obtained.

3. Results and Discussion

Resultant λ' values were studied in terms of the width to thickness ratio of the brace and the slenderness ratio of the brace to come up with an expression to calculate λ' value straight away for a given brace. Figs. 11 and 12 delineate the variation of λ' values with slenderness ratio *KL/r* and width to thickness ratio *d/t* respectively for the 50 models.

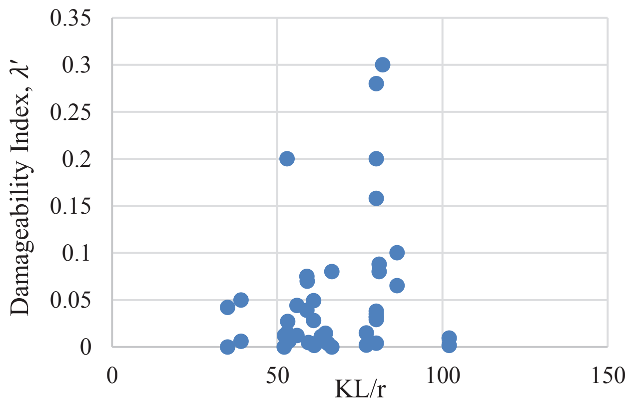

Figure 11: Variation of the modified damageability index λ' with d/t

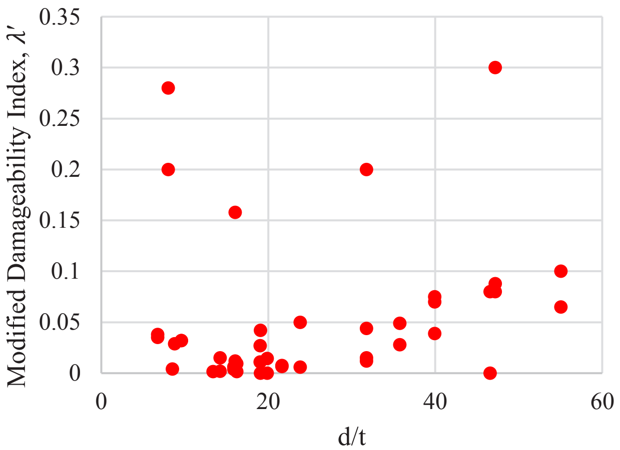

Figure 12: Variation of the modified damageability index λ' with d/t

Using statistical analysis in the form of a multiple regression model, a relationship for λ' was obtained in terms of brace width to thickness ratio *d/t.* It is important to note that the slenderness ratio was not a significant variable in the regression analysis and was omitted in the final expression as given in Eqn. 8.

$$\lambda' = 0.0015\left(\frac{d}{t}\right) \quad \text{….(8)}$$

4. Conclusion

It is clear that the fibre beam-column element employed within the OpenSees framework can predict the global behavior of the braces accurately. In addition to that, the fiber beam-column element is computationally robust when compared to the shell element in the present study. The inability of fiber beam-column elements to predict the local structural response was clearly observed and the limitation in applying CVGM directly using the resultant stress and strain histories was also evident. However, using a new modified damageability index λ', the failure prediction can be achieved in the modified CVGM. The use of the fiber beam-column element together with the modified CVGM can analyze braces in a multi-story building very effectively followed by a proper time history analysis. Users can determine whether the braces might experience fracture under a given earthquake level once a detailed history of stress and strains generated through fiber beam-column element is present.

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