A Study on Simulation Models of Seismic Energy Absorbing Steel Pipes

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Abstract*—The aim of this study is to develop simulation models of steel pipe as hysteretic dampers for seismic resistant steel structures. Steel pipe dampers are chosen as energy dissipating device because they are easy to install, maintain and inexpensive. Steel pipes in various positions are able to dissipate seismic input energy in a structure through hysteresis of the metal. Numerical simulation is carried out using nonlinear structural analysis program ABAQUS. Cyclic shear loading is applied to: a) vertical steel pipe dampers positioned in the plane of the frame of the structure; and b) horizontal steel pipe dampers positioned perpendicular to the plane of the frame of the structure. Cyclic axial loading is applied to the horizontal steel pipes positioned in the plane of the frame of the structure; in this case the steel pipes are intended to function as stoppers to backup the main damper in absorbing excessive seismic input energy. The following requirements for steel pipe dampers are taken into account: a) dampers provide stiffness and supplement damping to the structure; b) most part of the dampers yield simultaneously; c) dampers have satisfactory ultra low-cycle fatigue (ULCF) capacity. Steel pipes with diameter greater than 100 mm (considered to be useable as dampers) have diameter to thickness ratio more than 20 which is too slender; meaning, steel pipes have less than necessary amount of material to fulfill the above requirements. Various strengthening strategies to bare steel pipes are explored in the simulation models. Ductile fracture in steel that initiates in fewer than twenty constant amplitude loading cycles has been term Ultra Low Fatigue Cycle. Under ULCFs load dampers experienced extensive plasticity and limited cyclicity. ULCF has been treated more as a fracture problem than a fatigue problem in micromechanics-based models, which provide accurate criteria for predicting ductile fracture, proposed by Kanvinde and Deierlein (2007). Ductile fracture controls the ultimate strength and ductility of structural components, therefore accurate preliminary prediction of ductile fracture is critical to the performance of steel pipe dampers. The finite element simulation models can be utilized to preliminary predict ductile fracture in steel pipes using the criteria from the micromechanics-based models. Several results from studying the behavior and preliminary ductile fracture prediction of the models, which show the potential to be developed further into operational hysteretic steel pipe dampers, will be presented.

Keywords*—*ductile fracture, micromechanics-based model, steel pipe as hysteretic damper, supplemental damping

I. INTRODUCTION

In this paper, the results of a try-out research to investigate the potential of circular steel pipes as metallic dampers are presented. Energy dissipation of steel pipes in three pipe positions was investigated. Steel pipes dissipate energy : (i) due to cyclic shear loading in vertical position, or in horizontal position perpendicular to the plane of drawing and (ii) due to axial crushing in horizontal position in the plane of drawing. Ductile behavior of circular steel pipe dampers was simulated using finite element analysis. The hysteresis behavior of the circular steel pipe dampers will be shown and discussed.

For component integrity assessment of circular steel pipe dampers, finite element ductile failure simulations based on local approach was conducted. *Stress Modified Critical Strain (*SMCS*) model* was used to predict fracture. Two criteria were used for fracture analysis: (i) von Mises yield criterion was used to identify spots with intense stresses and (ii) SMCS criterion was used to predict fracture at the identified spots. Component integrity assessment was done for some potential candidate of good dampers.

II. HYSTERESIS BEHAVIOR OF CIRCULAR STEEL PIPE DAMPERS

A good circular steel pipe damper is expected to exhibit: (i) adequate elastic stiffness to withstand in-service lateral load, (ii) a yield strength of the damper exceeding the expected in–service lateral loads, (iii) large energy dissipative capability and (iv) a stable hysteretic force–displacement response which can be modeled numerically.

Maleki and Bagheri (2010) did some tests to the material of steel pipes. For pipe of diameter (d) 114 mm and thickness (t) 5 mm, the results of the test are shown in the Table I. The mechanical properties of this pipe were used in this study. Besides material data, monotonic loading used by Maleki and Bagheri (2010) is also used in this study. Monotonic loading consisted of steadily increasing the displacement up until 30 mm in 64 seconds. This loading consisted of two cycles at $\pm 0.3M$, $\pm 0.6M$, $\pm 0.9M$ (where M is the estimated yielding capacity) and then increasing the displacement up until 30 mm to investigate the hysteresis behavior of the dampers.

TABLE I. PROPERTIES OF STEEL PIPE USED IN THIS STUDY

d (mm)	t (mm)	E (GPA)	σ_y (MPa)	σ_u (MPa)	ε_u (%)
114	5	200	320	385	0.25

A. *Vertical Steel Pipe Dampers*

The size of the pipe damper was determined based on:

- Practical consideration. The damper was assumed to be installed at the apex of Chevron braces. From practical consideration, steel pipes with diameter greater than 100 mm were considered to be useable as dampers. In this study the steel pipe of 114.3 mm diameter was chosen.
- Most part of the pipe yield due to simulated incremental amplitude loading. Abebe, Kim and Choi (2013) demonstrated that in order the developed stresses both bending and shear stresses are occurred simultaneously the height to diameter ratio of the pipe should be equal to √3. Therefore the height of the pipe is equal to √3x114.3=197.97 mm ~ 200 mm.

The steel pipe having d = 114.3 mm, t = 5.6 mm and h = 200 mm will be used in the elastic-plastic simulation.

The displacement criteria for evaluating the performance of the damper were determined based on damage control of structures (Table II). If the typical floor height is assumed to be 3000 mm, the damage limit lateral displacement is15 mm and the collapse limit lateral displacement is 30 mm. Therefore it is expected that the steel pipe dampers are able to dissipate energy through hysteretic deformation of steel up to 15 mm displacement effectively without any fracture, but able to further dissipate energy up to 30 mm displacement in stable manner with some local fractures if they are unavoidable.

The simulation results of the bare pipe due to cyclic loading is shown in Fig. 1. It can be seen that the pipe buckles at the top and bottom supports and the hysteresis loop is unstable. Two strengthening strategies to the bare steel pipe are explored in the simulation models as follows: (i) strengthened with tapered plates welded at outer wall of the pipe as shown in Fig. 2 and (ii) strengthened with tapered plates welded to the outer wall of the pipe and lead filled inside the pipe as shown in Fig. 3. The last one is considered as a good candidate to be verified by specimen test in laboratory.

TABLE II. DAMAGE CONTROL OF STRUCTURES

Drift vs Limit	Damage limit	Collapse limit
Inter story drift	h/200	h/100

B. *Horizontal Steel Pipe Dampers Perpendicular to the Plane of the Drawing*

Maleki and Bagheri (2010) showed that bare steel pipes in horizontal position were able to dissipate energy and were very ductile. The only drawback of bare steel pipes is they are too flexible. Therefore, the pipes need to be strengthened in order to increase their strength and stiffness while maintaining their inherent ductility. The dampers were assumed to be installed at the apex of Chevron braces. The same pipe (114.3 x 5.6 x 200 mm) was used in the simulation. One option of strengthening the horizontal pipe with three inner rings is shown in Fig. 4.

C. *Horizontal Steel Pipe Dampers in the Plane of the Drawing*

Alexander (1959) analyzed a single pipe to absorb energy due to impact loading. He showed that the pipe was able to absorb significant amount of energy through axial crushing. The assumed collapse mode is shown Fig. 5. It can be seen that impact energy are absorbed by many plastic hinges formed at the joints of the folded pipe. He showed that half of plastic folding wave, h, is equal to $h = 1.213\sqrt{(Dt)}$ and the crushing load, P, is equal to $P = KYt^{1.5}\sqrt{D}$; where $K = 6.08$, Y is the yield stress of the steel, t is the pipe thickness and D is the diameter of the pipe.

Therefore pipes in horizontal position could be considered as secondary dampers to resist axial impact load due to earthquake. The secondary damper acts as stopper to back up to the main damper in absorbing energy. When the pipes dissipate energy through axial folding, they create sudden shocks which have harmful effects to the building and its content including the people during earthquakes. The simulation shown in Fig. 6 shows two horizontal pipes in horizontal position experience axial folding due to cyclic lateral load. There are two gaps of 10 mm at both free ends of the pipes. It can be seen that both pipes dissipate energy through axial crushing (folding). Besides sudden shocks, when the pipes fold the pipes shrink rapidly the gaps at the free ends of the pipes get bigger and bigger. Only very thin pipe (about 1 mm) with diameter about 50 mm that can dissipate energy with acceptable shock. However such a thin pipe is not available in the market. Horizontal pipes in the market to day are too thick to be used as stoppers. Therefore the potential of the horizontal pipe as stopper will not be explored further.

III. COMPONENT INTEGRITY ANALYSIS

A simple criterion has been established to predict the failure of the steel pipe dampers due to the interaction effect of fracture and fatigue known as ULCF. Fracture occurs when micro voids initiating at sulphide or carbide inclusions grow under plastic strains, leading to micro void coalescence. Stress Modified Critical Strain (SMCS), developed based on the concept of tracking micro void growth and coalescence, is one of such criteria (Kanvinde and Deierlein, 2007). In SMCS model, a critical value of plastic strain, $\varepsilon_p^{critical}$, is related to stress triaxiality, T, as $\varepsilon_p^{critical} = \alpha \cdot \exp(-1.5T)$. Triaxiality is the ratio between the hydrostatic (dilational) stress, $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$, and von Mises (distortional) stress, σ_e. The SMCS criterion, defined as the different between the critical plastic strain and the calculated equivalent plastic strain (ε_p), is SMCS = $\varepsilon_p - \varepsilon_p^{critical}$. Fracture is predicted to occur when SMCS = 0. SMCS model is simple to be applied to preliminary predict when ductile fracture will occur under ULCF condition.

For ductile fracture prediction in this try-out research, the circumferentially notched tension bar (CNT), extracted from the pipe, used by Myers, Deierlein and Kanvinde (2009) was simulated (Fig. 7). Ramberg Osgood model was used to model the strain hardening of the material. Because specimen test has not been done, the fracture displacement (Δ_f=0.92 mm) found by Myers, Deierlein and Kanvinde (2009) was used to calculate the equivalent plastic strain (ε_p=0.8) and the material resistance to fracture (α=2.39). Once α is determined, it can be implemented through finite element simulations to predict facture initiation in steel pipe dampers. Here is an example, for model in Fig 4 the results of the simulations showed that T = 0.35 and $\varepsilon_p^{critical}$ = 1.41 which corresponding to t = 56.3 sec and fracture initiation is expected to occur at 22 mm of lateral displacement. The stress triaxiality versus time plot is shown in Fig. 8.

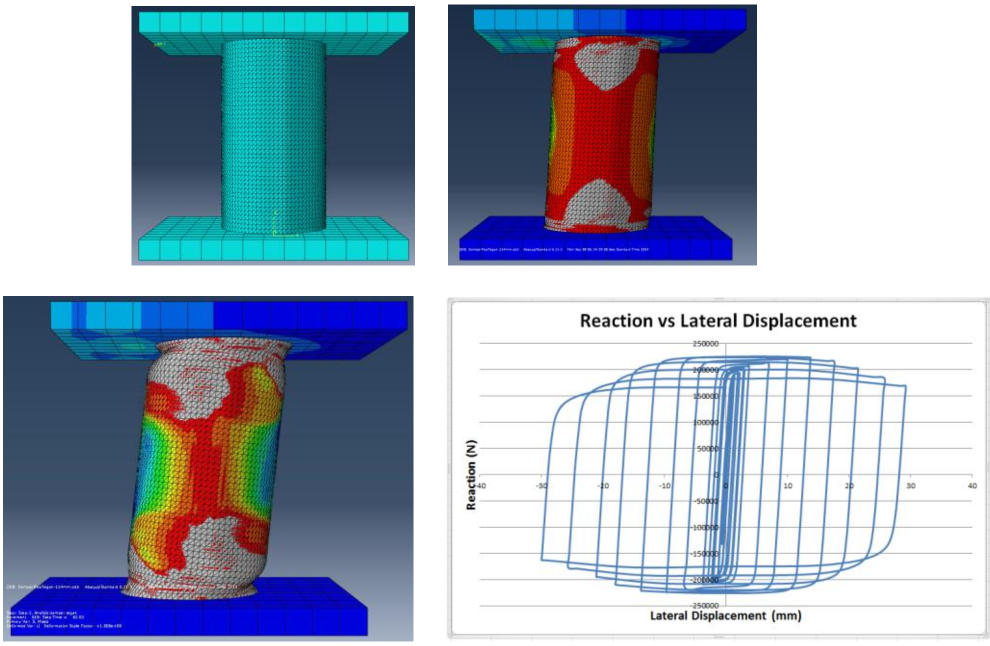

Fig. 1. Vertical steel pipe dampers: bare pipe damper. The Mises plots are for 14 mm and 30 mm of lateral displacement. Severe buckles occur at the top and bottom of the pipe at 30 mm lateral displacement. The hysteresis loop is fat but unstable.

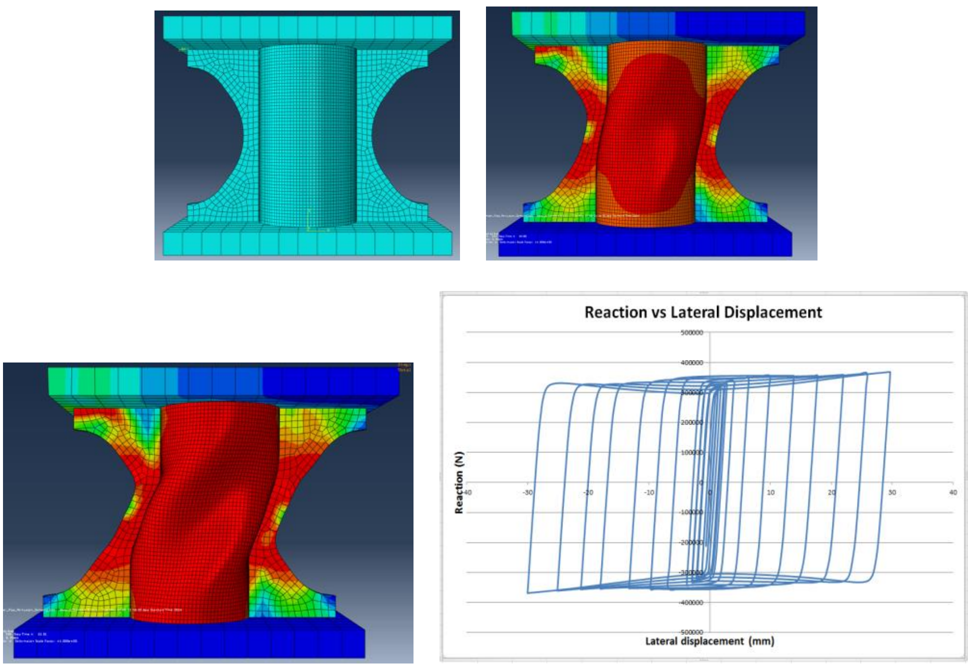

Fig. 2. Vertical steel pipe dampers: strengthened with tapered plates welded at outer sides of the pipe. The Mises plots are for 14 mm and 30 mm of lateral displacement. The tapered plates increase the capacity of the damper, however the middle part of the pipe buckles. The hystersis behavior is better but the loop is still unstable.

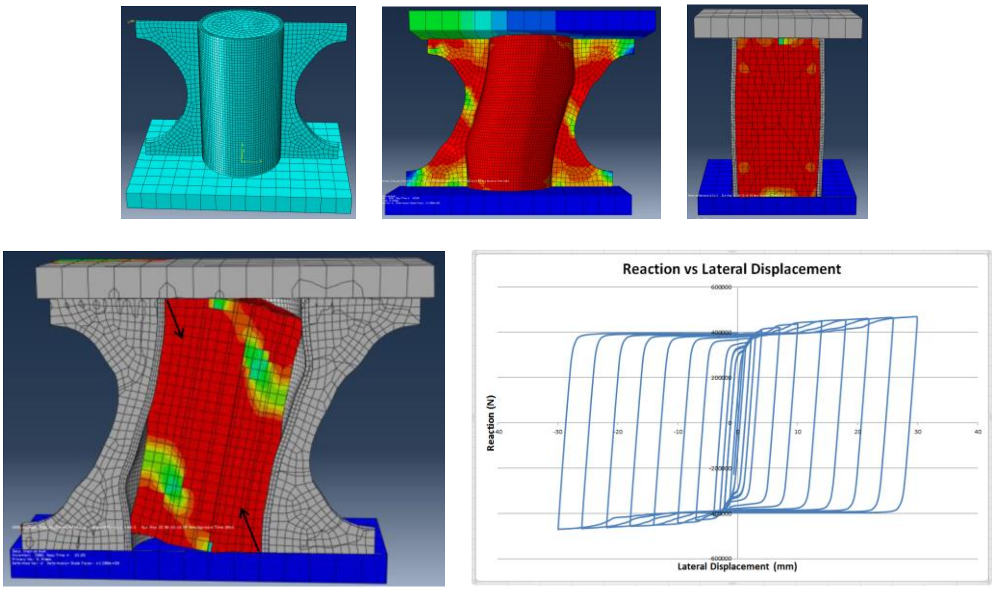

Fig. 3. Vertical steel pipe dampers: strengthened with tapered plates and lead filled inside the pipe (upper support plate is not shown). It can be seen that the lead reduce the buckle at the middle part of the pipe and dissipate energy through diagonal compression strut.

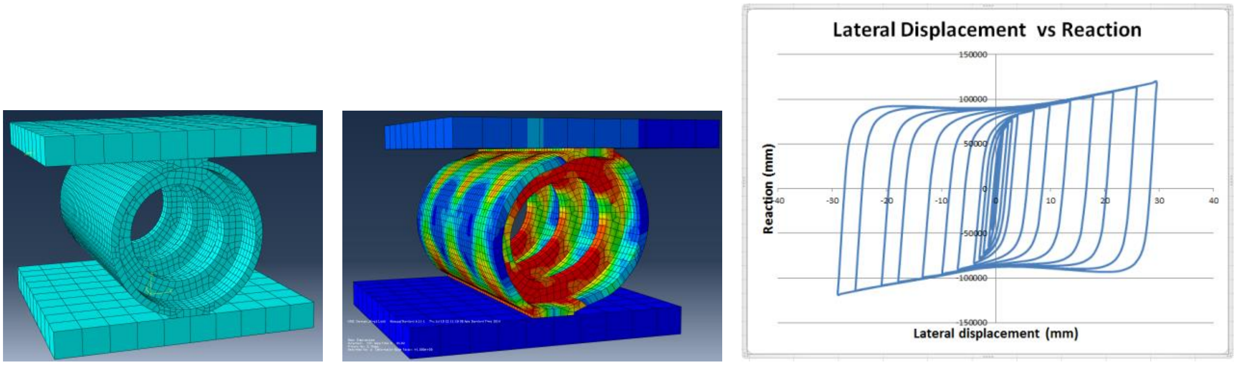

Fig. 4. Horizontal steel pipe dampers strengthened with three inner rings. The inner rings are welded to the pipe.

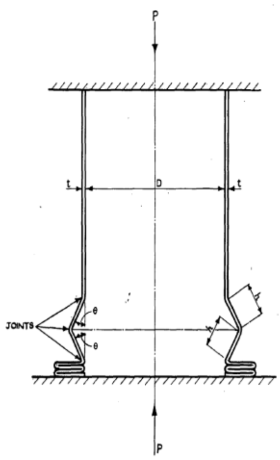

Fig. 5. Assumed collapse mode [3]

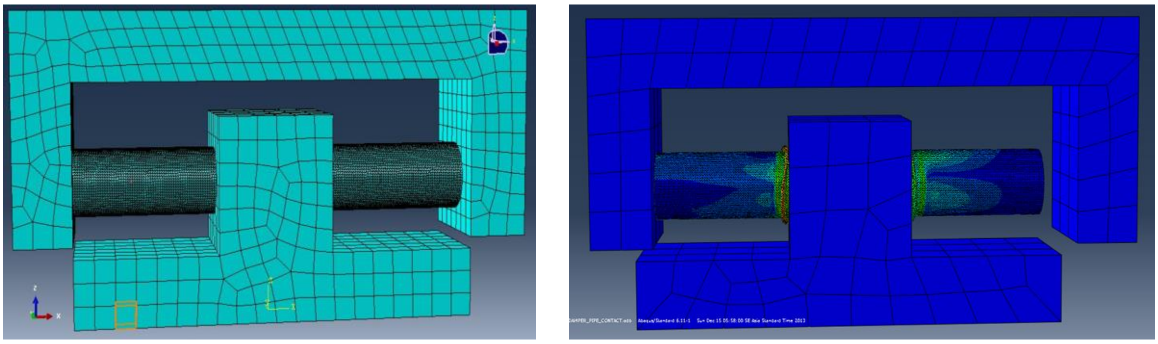

Fig. 6. Horizontal steel pipes as secondary dampers (axial crushing)

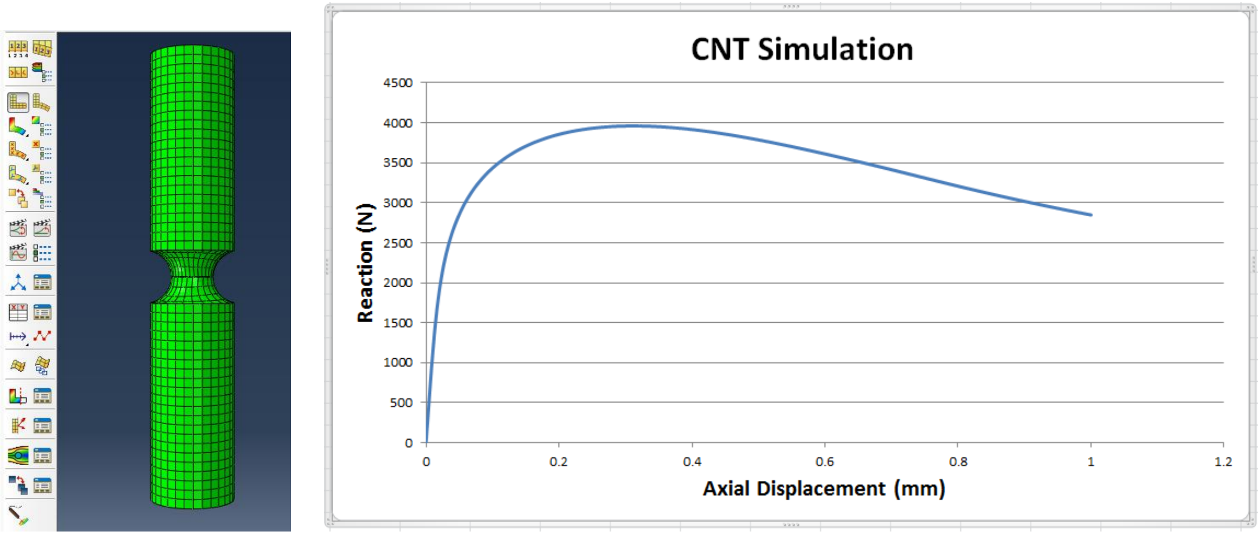

Fig. 7. Circumferentially notched tension bar (CNT) simulation

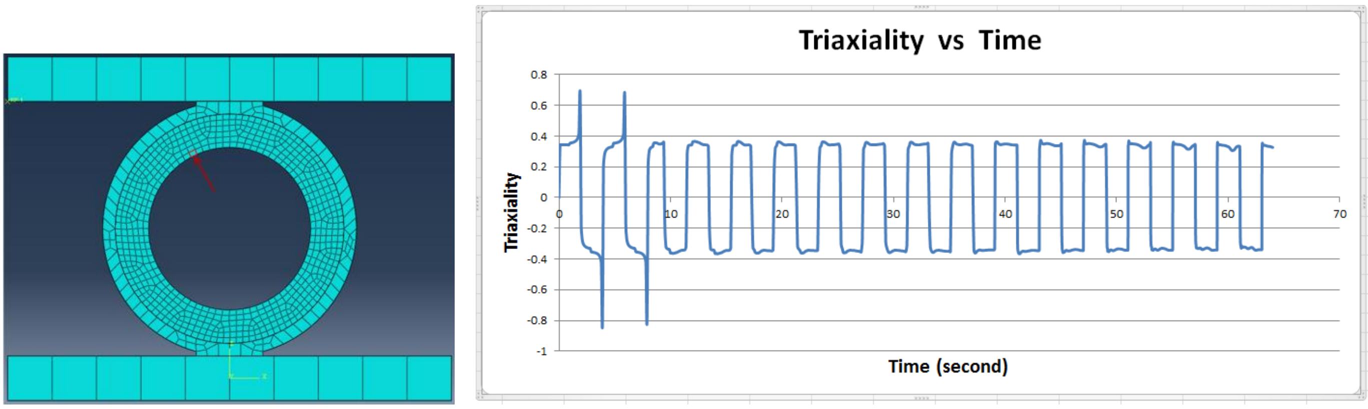

Fig. 8. Stress triaxiality vs time plot for the point of intense stress at the inner side of the ring (at the proximity of top and bottom supports). It can be seen in the right part of Fig. 8 that the stress triaxiality is constant ($T \sim 0.35$). The micro voids due to cyclic deformation grow and shrink repeatedly in the ring-pipe damper.

IV. Conclusion

This paper presented the results of numerical simulation conducted on circular steel pipe dampers in vertical and horizontal positions. The main findings of this study may be summarized as follows:

(1) The steel pipes have the potential as excellent metallic dampers in vertical and horizontal positions at the apex of Chevron braces. The dampers have fat and stable hysteretic curves. Therefore the dampers can be expected to reduce earthquake forces, lateral deformations, and to reduce or eliminate ductility requirements.

(2) Some strengthening strategies to the bare steel pipes are needed to improve the hysteresis behavior of the dampers and to postpone the onset of the ductile fracture in the dampers. For steel pipe damper strengthen with lead filled inside the pipe, if local fractures occur in the pipe the additional energy dissipation by the lead will substitute the loss of energy dissipation capacity of the damper due to the local fractures in the pipe (Fig. 3).

(3) To verify the actual hysteretic behavior of the studied steel pipe dampers specimen tests in laboratory are needed.

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