Influence of Slenderness Ratio and Sectional Geometry on the Behavior of Steel braced Frames

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ABSTRACT

Diagonal bracings are installed in frame structures, functioning as members for lateral resistance and energy dissipation. The objective of this study is to assess the hysteresis response behavior of circular hollow steel bracing. Energy dissipation, a key consideration in choosing brace parameters, plays a crucial role in enhancing seismic performance. This study highlights the cyclic response of three Finite Element (FE) modeled steel braces with variable steel diameter and wall thickness. The design method is additionally confirmed through FE models experiencing hysteresis loadings, suggesting that this approach can secure the overall stability of bracing and is well-suited for practical engineering implementations.

Keywords-energy dissipation; diagonal bracings; Circular Hollow Steel (CHS); ABAQUS

I. INTRODUCTION

Before the 1970s, the design of many structures focused on their ability to withstand gravitational loads. Although they were capable of bearing such weights, it was uncertain if they would withstand seismic loads [1]. Various methods can be employed to improve the resistance of Reinforced Concrete (RC) structures against lateral loads. Among these methods, the most prevalent and effective approach involves reinforcing steel structures through the implementation of bracing systems [2]. Steel-braced frames are recognized as one of the most cost-effective and efficient lateral load resisting systems for controlling deformations in civil structures subjected to earthquake or wind loading [3]. Using steel bracing is an efficient approach for strengthening buildings [4]. One of its benefits includes the ability to adapt to openings and its lightweight nature that imposes minimal additional weight on the structure [5].

Tubular design can be utilized to symbolize modern architecture and it is extensively employed in airports, stadiums, transmission towers, pylons, and similar structures [6]. Closed and curved sections, such as elliptical, circular, and oval shapes, are recognized for offering increased torsional rigidity and exceptional compression behavior. They provide local strength against impact loading [7]. In the last two decades, researchers have developed and utilized various testing protocols to evaluate the performance of cyclic structural members. Cross-type braces are linked to the beam-to-column connection joints, whereas K-type braces are attached to the midpoints of beams and columns. Furthermore, the selection of brace configurations depends on the intended purpose of buildings. Cross-type bracing is appropriate for closed panels, while K-type bracing is appropriate for windows [8]. The most effective methods for enhancing the resistance to lateral loading during earthquakes involve the utilization of steel bracing. This approach is proved to be effective in strengthening earthquake-damaged buildings and improving the load-resisting capacity of the RC structures [9]. Bracing members that experience compressive forces from a moderate to severe earthquake are prone to buckling, playing a role in the dissipation of energy [10]. Steel braced frames are typically utilized to ameliorate stiffness and resistance against lateral forces. When these frames are introduced, they serve as a means to absorb and dissipate energy during seismic activity. In the Special Concentrically Braced Frame (SCBF) system, three hinges are created within the braced structure to enhance ductility and facilitate the dissipation of energy [11]. Braces deform plastically under tension and experience buckling under compression, while columns and beams are typically considered to stay within the elastic range. Numerous experiments and analytical studies have been conducted to assess the seismic performance of steel-braced structures [12-14].

This study specifically focuses on circular hollow steel bracing, while other works might explore different types of bracing materials (such as concrete or cables) or brace configurations (such as X-bracing or K-bracing). Comparing the performance of circular hollow steel bracing to alternative materials or brace types could provide insights into the relative advantages and disadvantages of each option in terms of seismic performance, cost-effectiveness, and ease of construction. By juxtaposing this work with other relevant studies, researchers can gain a more comprehensive understanding of the behavior and performance of circular hollow steel bracing and identify opportunities for further research and improvement. Comparisons could be made with studies that examine the performance of bracing systems under different loading scenarios, such as wind loads or blast events. Understanding how circular hollow steel bracing performs under various dynamic loading conditions related to other bracing systems, can help assess its versatility and effectiveness in different structural contexts.

Authors in [15] conducted dynamic and static tests on frames incorporating braces, demonstrating that the installation of bracing enhanced a frame's ability to dissipate energy. They demonstrated that the primary frame retained its elastic behavior even under significant earthquake loads. Previous seismic events have revealed that brace frame systems are vulnerable to premature collapse. Several undesirable failure modes, including the fracture of the interface weld of the gusset plate, tearing of the gusset plate, buckling of the gusset plate, net section failure of the brace cross-section, and premature failure of the brace section, have been observed [16]. Based on the data gathered from both real seismic events and experimental assessments [17-20], it has been determined that there are three specific locations within the braced frame that are susceptible to damage [19]. Previous research conducted on both I-shaped bracing members [21–24] and rectangular hollow bracing members [25-29] indicates that the geometric characteristics of these bracing components play a crucial role in determining their performance under low-cycle fatigue conditions.

II. THE SLENDERNESS RATIO

The slenderness ratio (λ) of a structural member is described as the ratio of its effective length to the minimum radius of gyration. Due to its circular shape, Hollow Structural Sections (HSSs) possess the practical advantage of being able to withstand loads in all directions. This is particularly beneficial in practical situations, as it enables the structure to effectively resist forces in multiple dimensions, e.g. during earthquakes. The prevailing conclusion from [30] indicates that the global slenderness significantly influences the hysteretic behavior of braces. Slender members tend to lose compressive resistance at a faster rate compared to stocky members, leading to fewer cycles of inelastic response and lesser energy dissipation.

Circular Hollow Sections (CHSs) and Square Hollow Sections (SHSs), are optimal as compression members for preventing overall (global) buckling because they do not have a "weak axis", in contrast to open sections [31]. The seismic performance of bracing elements is mainly affected by two crucial factors: The effective slenderness ratio and the D/t ratio. Specifically, braces with larger cross-sectional dimensions exhibit a lower slenderness ratio. The reduction in slenderness ratio is associated with a decrease in the ultimate load capacity [32]. In general, the non-dimensional global slenderness ratio λ is among the most crucial parameters that can be correlated with cyclic energy dissipation and fracture life. λ is defined as follows [30, 33]:

$$\lambda = k\,l / r \quad (1)$$

$$r = \frac{\sqrt{d^2 + d1^2}}{4} \quad (2)$$

where l is the bracing member length, K is the brace-effective length factor, r is the governing radius of gyration, d is the outer diameter of the circle, and d1 is the inner diameter of the circle.

The global slenderness of the braces is limited to the following as given in ANSI/AISC 341-16:

$$\frac{kl}{r} \leq 4\sqrt{\frac{E}{Fy}} \quad (3)$$

where E is the modulus of elasticity of steel (200 Gpa) and Fy is the specified minimum yield stress to be used (348 Mpa).

III. CASE STUDY

A. Brace Characteristics

The diameter of the 3D circular hollow steel members was taken as 6 3mm, 127 mm, and 244mm respectively for each member with constant brace thickness of 6.35 mm. Three braced members were designed to evaluate the effectiveness of CHS bracing members and their behavior was compared. The modulus of elasticity of steel was equal to 200000 MPa, with a yield stress of 348 Mpa. The plastic material parameters for steel tubes were: Ultimate Tensile Strength (UTS) equal to 420 MPa, steel Poisson’s ratio was assumed as 0.3, hardening modulus was 1.94 GPa, and the density was 7850 kg/m^3. Design and calculations were based on AISC provisions. The analytical study was carried out on the ABAQUS Mechanical APDL software package. All the braces were made of ASTM A500 Grade B steel with modeling members of cold-rolled carbon steel.

B. Non-linear Finite Element Analysis

CHSs were selected and analyzed with the ABAQUS 3D Finite Element (FE) analysis package. Material nonlinearity was incorporated into the FE model. Both solid and shell element models were tried to determine the most suitable element for simulating the behavior of the pipe. Various mesh sizes were investigated to identify a suitable mesh that delivers accurate results while minimizing computational time, as illustrated in Figure 1. All rotational and translational displacement components were constrained at the reference points of the lower end plate. A cyclic load was applied to the reference points at the upper end plate in the Z-direction, whereas the whole translation and rotation in other directions were fixed. Stress concentration is obvious at both ends in the loading direction, with the maximum stress observed at the lower ends in the loading direction.

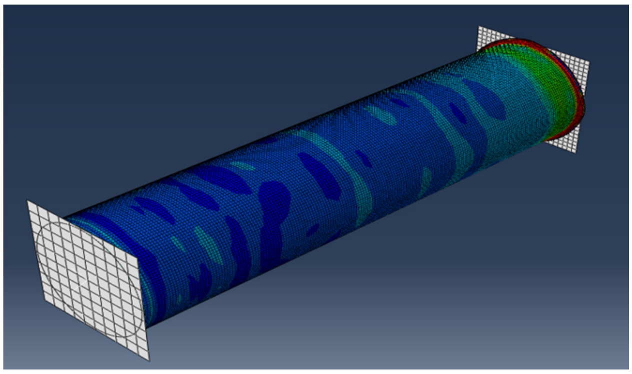

Fig. 1. Response of braces obtained in ABAQUS.

For accurately predicting the behavior of HSS bracing and compression components, the longitudinal mesh span was set to 5 elements at the midpoint, as displayed in Figure 2, for a typical bracing model. A similar methodology was employed for meshing both ends of the brace models, with the span set to 10 elements.

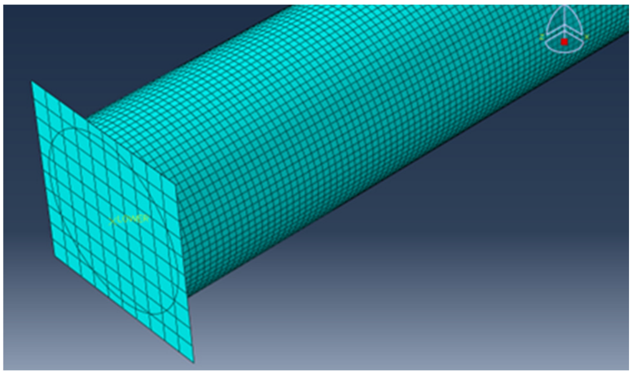

Fig. 2. FE mesh pattern.

The nodes at both ends of the members were constrained, with the exception of axial displacement at the loading end, which was allowed for translational movement along the global axis, as illustrated in Figure 4.

The nodes at both ends of the members were constrained, with the exception of axial displacement at the loading end, which was allowed for translational movement along the global axis, as can be seen in [6]. Once the steel tubes were subjected to axial loading, the cyclic lateral load was subsequently applied at the upper section, following the designated loading protocol. The cyclic loading protocol implemented followed to the ECCS recommendations [24]. In this protocol, the incremental rise in cyclic horizontal displacement, denoted as d, is contingent upon the known yield displacement δ_y [33]. The loading was initiated at the end through a Reference Point (RP), which served as the principal point for all circumferential nodes of the model within the loading plane.

IV. RESULTS AND DISCUSSION

In practical terms, understanding the relationship between axial strain and energy dissipation is crucial in designing and analyzing the performance of materials and structures, especially in applications where cyclic loading or deformation is involved. Figure 3 explains how the cumulative energy dissipated per load step varies with the axial strain level of braces, considering a specific diameter value and varying values of the slenderness ratio. The cumulative energy is calculated by determining the area surrounded within the hysteresis loops for all the cycles at each axial strain level. The magnitude of energy dissipation gradually increases with the axial strain level for the brace having a slenderness ratio of 7. An augmentation in the slenderness ratio leads to a decrease in the cumulative energy due to the fracture of braces. Braces with slenderness ratios of 14 and 22 exhibited a lower level of energy dissipation.

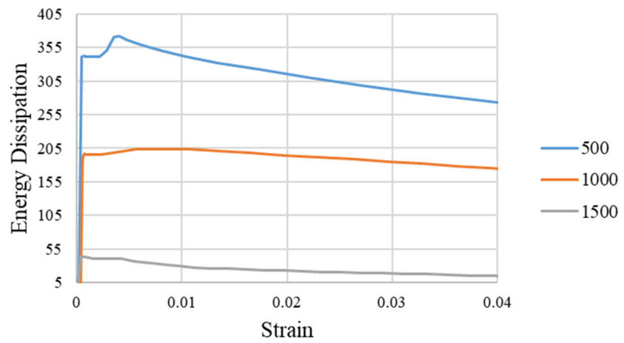

Fig. 3. Energy dissipation versus D/t.

To expand the assessment of the circular hollow steel, an analytical study was conducted to investigate the impact of the diameter-to-thickness ratio (D/t). The D/t is the main parameter under consideration in the non-linear FE analysis. The response of a CHS steel bracing depends on D/t. The plot of cumulative energy versus the diameter-to-thickness ratio is depicted in Figure 4. Cumulative energy decreases with an increase of D/t.

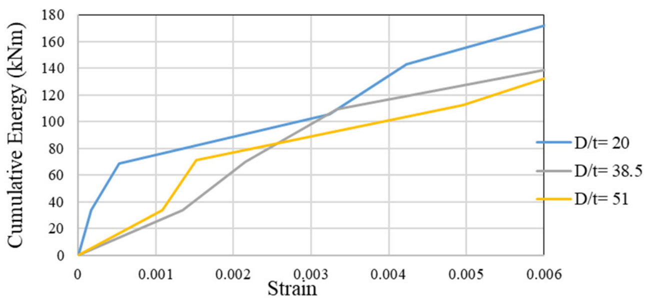

Fig. 4. Cumulative energy versus D/t.

The load-displacement relationship for bracing in buildings typically refers to the behavior of bracing elements under different loads and corresponding displacements. Bracing systems are commonly used in structural engineering to provide lateral support and resist forces, such as wind or seismic loads. The load-displacement curve for the bracing systems is influenced by various factors, including the type of bracing, material properties, and the structural configuration.

Figure 5 depicts the hysteresis curves for the load displacement in three representative CHS FE models. These models have a length of 1000 mm and different *D/t* ratios. It is observed that CHS models with high *D/t* ratios exhibit increased post-buckling compressive resistances. Positive values on the vertical axis represent tension and negative represent compression. Furthermore, smaller diameter sections demonstrate greater displacement. In all models, the compressive resistance decreases after successive loading cycles due to the accumulated elongation and residual lateral deformation at the plastic hinge near mid-length. The load-displacement relationship is a crucial aspect of structural analysis and design, helping engineers ensure that buildings can withstand anticipated loads while providing a predictable and controlled response to external forces. Structural engineers use this information to design buildings that meet safety standards and performance requirements.

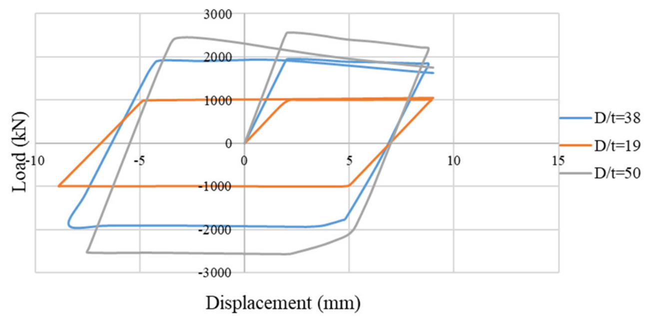

Fig. 5. Load-displacement hysteresis loops of CHS brace models obtained in the current FE study.

V. CONCLUSION

This study focuses on evaluating the hysteresis response behavior of circular hollow steel bracing, which is commonly deployed in frame structures for lateral resistance and energy dissipation during seismic events. The research examines the cyclic response of three finite element modeled steel braces with variable steel diameter (D) and wall thickness (t). The objective is to understand how these parameters impact energy dissipation and seismic performance. The findings suggest that the design method, confirmed through finite element models experiencing hysteresis loadings, is effective in ensuring the overall stability of bracing and is suitable for practical engineering applications. The study provides valuable insights for practical engineering implementations, offering a potentially more efficient and effective approach to securing the overall stability of bracing in structures. Based on the obtained values from the analytical study, the following conclusions can be extracted:

- The effective slenderness ratio of the brace is decreased when the CHS diameter is increased, although the fracture life and energy dissipation capacity are differently affected.
- The influence of the braces was found to depend on the specific brace dimensions employed.
- Sections characterized by a greater D/t ratio typically demonstrate decreased lateral deflection.
- Sections with higher slenderness ratios manifest lower energy dissipation values across all levels of ductility.

This analysis helps understand how different design parameters influence the energy dissipation and seismic resistance, furnishing meaningful input for optimizing brace design in real-world applications. By demonstrating the effectiveness of the design method for enhancing the overall stability of bracing, the study offers practical implications for engineering applications. Engineers and designers can utilize the insights gained from this research to improve the seismic performance of frame structures in real-world scenarios.

Understanding the hysteresis response behavior of circular hollow steel bracing and its relationship with energy dissipation is crucial for enhancing the seismic performance of structures. This study adds to the body of knowledge aimed at developing more resilient and earthquake-resistant building systems, contributing to advancements in seismic engineering practices.

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