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NUMERICAL INVESTIGATION OF THICKNESS AND MATERIAL EFFECTS ON THE MECHANICAL BEHAVIOR OF MILD STEEL DAMPERS USING FINITE ELEMENT ANALYSIS

Iskandar Yasin[1,*]
Department of Civil Engineering, Faculty of Engineering
Universitas Sarjanawiyata Tamansiswa
Email: iskandaryasin@ustjogja.ac.id

Widarto Sutrisno[2]
Department of Civil Engineering, Faculty of Engineering
Universitas Sarjanawiyata Tamansiswa
Email: widarto.sutrisno@ustjogja.ac.id

Nurul Hasan[3]
Don Computing Pty Ltd,
Melbourne, Australia
Email: drnhasan@doncomputing.com

Andi Ibrahim Soumi[4]
Department of Mechanical Engineering, Faculty of Engineering
Universitas Sarjanawiyata Tamansiswa
Email: andi.soumi@ustjogja.ac.id

ABSTRACT

Mild steel dampers are widely utilized as energy dissipation devices due to their ductility and stable mechanical behavior. This study investigates the effects of plate thickness and material variation on the mechanical performance of an H-type mild steel damper using nonlinear finite element modeling. The model was developed in ANSYS using three-dimensional solid elements, incorporating both material and geometric nonlinearity to capture the structural response under quasi-static loading conditions. The quasi-static loading approach was adopted to represent gradual displacement-controlled behavior commonly used in damper performance evaluation. Two parametric studies were conducted, including plate thickness variations (15 mm, 20 mm, 25 mm, and 30 mm) and material variations (structural steel, grey cast iron, and aluminum alloy). The mechanical behavior was evaluated in terms of total deformation, equivalent von Mises stress, and equivalent plastic strain (PEEQ) along the damper height. The results indicate that increasing plate thickness significantly reduces deformation and plastic strain while improving stress distribution, reflecting enhanced structural stiffness. However, excessive thickness may reduce deformation capacity. In terms of material performance, structural steel exhibits the most stable response with low deformation and well-distributed stress and strain. Aluminum shows higher deformation and strain due to its lower stiffness, while grey cast iron demonstrates limited ductility and higher stress concentration. An optimal configuration is identified at a thickness range of 20-25 mm using structural steel, providing a balance between stiffness and deformation capacity. These findings contribute to the design optimization of metallic dampers for structural applications, particularly in quasi-static loading scenarios relevant to seismic-resistant systems.

Keywords: Mild Steel Damper, Finite Element Analysis, Plate Thickness Variation, Material Properties, Mechanical Behavior

ABSTRAK

Peredam baja lunak (mild steel dampers) banyak digunakan sebagai perangkat disipasi energi karena sifat keuletannya dan perilaku mekanik yang stabil. Penelitian ini mengkaji pengaruh variasi ketebalan pelat dan jenis material terhadap kinerja mekanik peredam baja lunak tipe H menggunakan pemodelan elemen hingga nonlinier. Model dikembangkan dalam ANSYS menggunakan elemen padat tiga dimensi, dengan mempertimbangkan nonlinieritas material dan geometrik untuk menangkap respons struktur di bawah kondisi pembebanan kuasi-statis. Pendekatan pembebanan kuasi-statis digunakan untuk merepresentasikan perilaku perpindahan bertahap yang umum diterapkan dalam evaluasi kinerja peredam. Dua studi parametrik dilakukan, yaitu variasi ketebalan pelat (15 mm, 20 mm, 25 mm, dan 30 mm) serta variasi material (baja struktural, besi cor kelabu, dan paduan aluminium). Perilaku mekanik dievaluasi berdasarkan deformasi total, tegangan ekuivalen von Mises, dan regangan plastis ekuivalen (PEEQ) sepanjang tinggi peredam. Hasil penelitian menunjukkan bahwa peningkatan ketebalan pelat secara signifikan menurunkan deformasi dan regangan plastis serta memperbaiki distribusi tegangan, yang mencerminkan peningkatan kekakuan struktur. Namun demikian, ketebalan yang berlebihan dapat mengurangi kapasitas deformasi. Dari sisi material, baja struktural menunjukkan respons paling stabil dengan deformasi rendah serta distribusi tegangan dan regangan yang lebih merata. Paduan aluminium menunjukkan deformasi dan regangan yang lebih tinggi akibat kekakuannya yang lebih rendah, sedangkan besi cor kelabu menunjukkan keuletan yang terbatas dan konsentrasi tegangan yang lebih tinggi. Konfigurasi optimal diperoleh pada rentang ketebalan 20-25 mm dengan menggunakan baja struktural, yang memberikan keseimbangan antara kekakuan dan kapasitas deformasi. Temuan ini berkontribusi terhadap optimasi desain peredam logam untuk aplikasi struktural, khususnya pada kondisi pembebanan kuasi-statis yang relevan dengan sistem tahan gempa.

Kata kunci: Peredam Baja Lunak, Analisis Elemen Hingga, Variasi Ketebalan Pelat, Sifat Material, Perilaku Mekanik

1. INTRODUCTION

Mechanical components designed for controlled deformation and energy dissipation have become increasingly important in modern engineering applications [1][2]. Among these, metallic dampers particularly mild steel dampers have been widely recognized due to their stable plastic deformation behavior, high ductility, and reliable mechanical performance [3]. These devices operate by undergoing controlled yielding, allowing them to absorb and dissipate external energy while protecting the primary structural components from excessive stress [4]. The effectiveness of steel dampers has been widely demonstrated in recent studies, where their ability to provide additional stiffness and energy dissipation has significantly improved structural performance under external loading conditions [5][6].

The mechanical behavior of mild steel dampers is strongly influenced by their geometric configuration and material properties [7]. In particular, parameters such as plate thickness, cross-sectional dimensions, and slenderness ratio play a crucial role in determining stiffness, load carrying capacity, and deformation characteristics [8]. Previous studies have shown that variations in geometric properties can significantly affect elastic stiffness, yield strength, and post yield behavior of dampers under loading [9][10][11]. In addition, material characteristics govern the yielding mechanism, ductility, and overall structural response. Different materials exhibit distinct mechanical behaviors, ranging from ductile responses in structural steel to brittle failure characteristics in cast iron, and lightweight yet lower-strength responses in aluminum [12]. Therefore, understanding the combined influence of geometry and material is essential for optimizing damper performance.

Despite extensive research on metallic dampers, most existing studies primarily focus on overall system performance or specific damper configurations without providing a comprehensive parametric evaluation of both thickness and material variations simultaneously [13]. Previous studies have extensively investigated the mechanical behavior and energy dissipation performance of metallic dampers through both experimental and numerical approaches. For instance, Farajiani et al. [14] U-shaped metallic damper study demonstrated that U-shaped metallic dampers exhibit stable hysteretic behavior and are capable of sustaining large inelastic deformations without significant strength degradation under cyclic loading conditions. Similarly, Zhou et al. [15] rotational metallic damper reported that rotational steel dampers provide high energy dissipation capacity with an equivalent viscous damping ratio exceeding 0.47, highlighting the importance of geometric configuration in enhancing damper performance.

In addition, several numerical studies have emphasized the significant influence of geometric parameters such as thickness and shape on the structural response of energy dissipation devices. Finite element-based investigations have shown that increasing structural thickness leads to enhanced stiffness and reduced deformation due to higher load-carrying capacity and moment of inertia effects [16]. Moreover, parametric optimization studies on metallic dampers indicate that geometric modifications can improve energy dissipation efficiency by up to 30%, particularly when combined with nonlinear material modeling [17].

From a material perspective, previous research has highlighted that the selection of material properties significantly affects the stress distribution, ductility, and overall performance of dampers. Advanced materials such as shape memory alloys (SMA) have been shown to provide higher stiffness, improved ductility, and superior energy dissipation compared to conventional steel dampers [18]. However, despite these advancements, most studies focus on either geometric optimization or material variation independently, with limited investigations addressing the combined influence of both parameters under consistent loading conditions. Furthermore, while finite element methods have been widely used to analyze damper behavior [19], detailed comparisons involving multiple material substitutions under identical geometric conditions remain limited. This indicates a clear research gap in understanding how different materials interact with geometric parameters to influence the mechanical response of dampers.

Finite Element Analysis (FEA) has emerged as a powerful and reliable tool for investigating the nonlinear mechanical behavior of structural components [20][21]. It enables detailed evaluation of stress distribution, deformation patterns, and plastic strain development under various loading conditions. Recent studies have demonstrated that FEA can accurately predict yielding behavior, post yield characteristics, and internal stress mechanisms in metallic dampers, making it an effective approach for parametric studies and design optimization [22] [23]. Compared to experimental methods, FEA provides greater flexibility in analyzing multiple design variables efficiently and economically.

Therefore, this study aims to conduct a numerical investigation of the mechanical behavior of mild steel dampers using finite element analysis. The research focuses on evaluating the effects of plate thickness variation (15 mm, 20 mm, 25 mm, and 30 mm) and material variation (structural steel, grey cast iron, and aluminum) on the structural response of the damper. The analysis is carried out under static loading conditions, with key parameters including stress distribution, total deformation, and equivalent plastic strain being examined.

The findings of this study are expected to provide a deeper understanding of the relationship between geometric parameters and material properties in damper design. Furthermore, the results will contribute to the development of more efficient and optimized mechanical components, particularly in applications requiring controlled deformation and reliable structural performance.

2. METHOD

2.1. Research Approach

This study adopts a numerical approach using the finite element method (FEM) to investigate the mechanical behavior of mild steel dampers under variations in plate thickness and material properties. The simulations are conducted using ANSYS R1 Static Structural, which enables the analysis of nonlinear material behavior under static loading conditions. The research workflow in figure 1 includes geometric modeling, material definition, mesh convergence verification, application of boundary conditions, nonlinear analysis, and evaluation of structural responses.

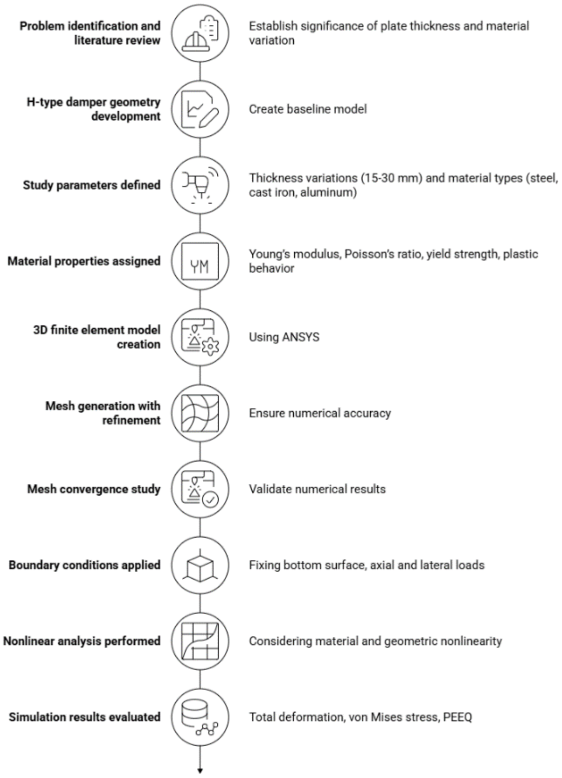


Figure 1 Schematic workflow

2.2. Geometric Modeling

The damper model is developed based on an H-type configuration consisting of web and flange plates, as illustrated in the reference design . The baseline geometry is adopted from a reference configuration with a plate thickness of 20 mm [13], which serves as the control model in this study. To investigate the influence of geometric parameters on the mechanical behavior of the damper, the plate thickness is systematically varied into four configurations, namely 15 mm, 20 mm, 25 mm, and 30 mm. These variations are intended to capture the effect of thickness on stiffness, load-carrying capacity, and deformation characteristics. Meanwhile, all other geometric parameters, including the overall height, width, and flange dimensions, are kept constant throughout the analysis. This approach ensures that any observed changes in the structural response can be attributed solely to the variation in plate thickness, thereby enabling a clear evaluation of its effect on the mechanical performance of the damper.

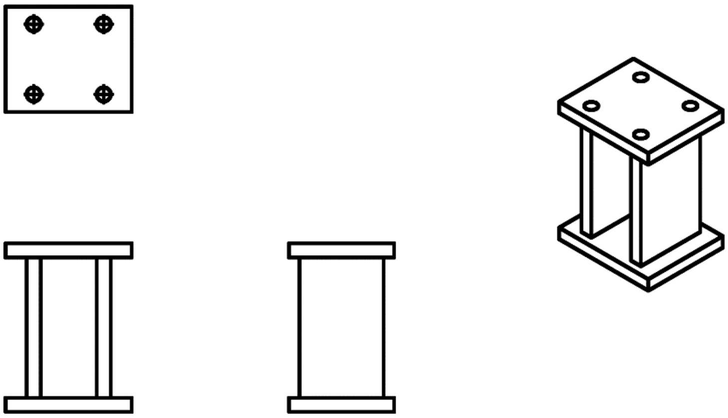


Figure 2 Part modelling

2.3. Material Properties

The material properties play a crucial role in determining the mechanical behavior of the damper, particularly in terms of stiffness, strength, and deformation characteristics. In this study, three different materials are selected to evaluate the influence of material characteristics on damper performance, namely structural steel, grey cast iron, and aluminum alloy. These materials are chosen to represent different mechanical behaviors, ranging from ductile to brittle responses, allowing a comprehensive comparison of their performance under identical geometric conditions.

Structural steel is used as the baseline material due to its widespread application in engineering structures and its well-known ductile behavior. It is modeled using a bilinear elastoplastic material model with isotropic hardening to accurately capture yielding and post-yield deformation. This approach enables the simulation to represent the strain hardening effect that typically occurs after yielding, which is essential for analyzing energy dissipation behavior.

Grey cast iron is selected to represent a brittle material with limited ductility. Unlike structural steel, grey cast iron exhibits minimal plastic deformation before failure, and its behavior is primarily governed by its elastic response followed by sudden fracture. In this study, it is modeled with linear elastic properties up to its yield limit, reflecting its brittle nature and low strain capacity.

Aluminum alloy is included as a lightweight ductile material with lower yield strength compared to structural steel. It is modeled using an elastoplastic material model to capture its deformation behavior under loading. Due to its relatively low stiffness and strength, aluminum is expected to exhibit larger deformation but reduced load-carrying capacity.

The material properties defined in the simulation include Young’s modulus, Poisson’s ratio, yield strength, and density. Nonlinear plasticity is applied to ductile materials (structural steel and aluminum alloy) to capture post-yield behavior, while grey cast iron is treated as a brittle material with limited plasticity. The material parameters used in this study are based on standard values available in the ANSYS material library and are summarized in Table 1.

Table 1 Material properties

Material	**Young’s Modulus (GPa)**	**Poisson’s Ratio**	**Yield Strength (MPa)**	**Density (kg/m³)**	**Material Behavior**	**Reference**
Structural Steel	200	0.30	250	7850	Elastoplastic (Bilinear)	[24][25]
Grey Cast Iron	110	0.26	130	7200	Linear Elastic (Brittle)	[26]
Aluminum Alloy	70	0.33	150	2700	Elastoplastic	[27]

2.4. Finite Element Modeling

The numerical model is developed using three-dimensional solid elements in ANSYS to accurately represent the geometric and mechanical behavior of the damper. Figure 3 illustrates the finite element mesh configuration applied to the H-type mild steel damper model. A refined mesh is applied in critical regions, particularly in the web area of the damper, where significant shear deformation and plastic strain are expected to be concentrated. This refinement is essential to ensure that the stress distribution and nonlinear responses are captured with sufficient accuracy. The modeling approach adopts a three-dimensional solid element formulation, with bonded contact defined between connected components to simulate a fully constrained interaction without relative slip. In addition, large deformation effects are activated to account for geometric nonlinearity arising from significant displacement during loading. To further ensure the reliability and accuracy of the numerical results, a mesh convergence study is conducted, as described in Section 2.5, in order to verify that the solution is independent of mesh size.

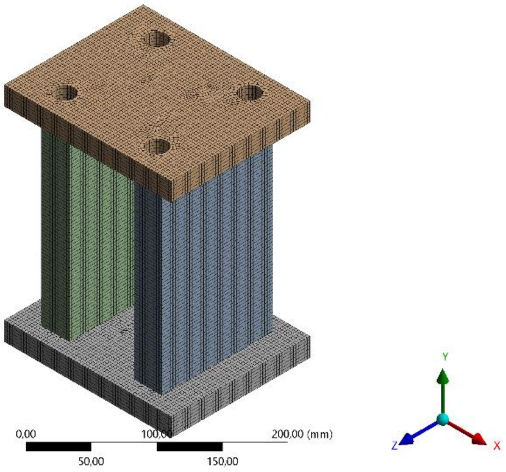


Figure 3 Meshing

2.5. Mesh Convergence Study

A mesh convergence study is conducted to verify the accuracy and stability of the numerical model. The mesh size is varied from 10 mm to 2 mm, and the corresponding total deformation values are recorded. Figure 3 shown grid refinement study. The results indicate that significant variations occur when coarse meshes are used, particularly between 10 mm and 5 mm. However, as the mesh is refined to 3 mm and 2 mm, the difference in total deformation becomes negligible, with percentage differences of 0.312% and 0.251%, respectively.

The convergence criterion is satisfied when the variation between successive mesh refinements is less than 1% [28]. Based on this criterion, a mesh size of 3 mm is selected for all subsequent simulations, as it provides a balance between computational efficiency and numerical accuracy.

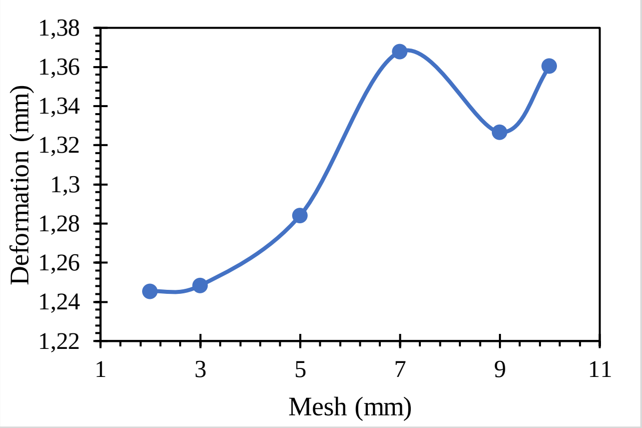


Figure 4 Grid Refinement Study

2.6. Boundary Conditions and Loading

Figure 4 illustrates the boundary conditions and loading configuration applied to the H-type mild steel damper model. As shown in the figure, the bottom surface of the damper is fully constrained, representing a fixed support condition that prevents both translational and rotational movements. This boundary condition simulates the anchorage of the damper to a rigid structural base. The boundary conditions are defined to simulate realistic mechanical loading on the damper:

a. The bottom surface of the damper is fully constrained (fixed support).
b. An axial load of 400 kN is applied vertically at the top surface.
c. A lateral load of 300 kN is applied in the horizontal direction using displacement control.

The maximum displacement is set to 72 mm, and the load is applied incrementally to capture nonlinear structural behavior.

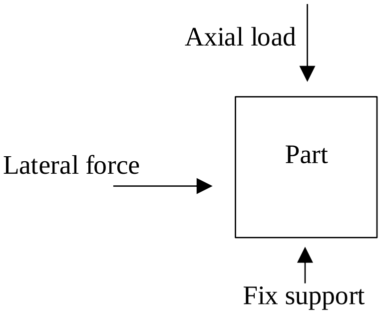


Figure 5 Boundary conditions

2.7. Nonlinear Analysis Settings

A nonlinear static analysis is performed to account for both material yielding and geometric nonlinearity during the loading process. In order to accurately capture these nonlinear responses, several analysis settings are implemented within the simulation. Large deformation effects are enabled to consider geometric changes resulting from significant displacements. Automatic time stepping is applied to ensure numerical stability by adjusting the load increments adaptively throughout the analysis. The loading is introduced incrementally using multiple substeps, allowing the model to progressively capture the transition from elastic to plastic behavior. In addition, the Newton–Raphson iterative solver is employed to solve the nonlinear equilibrium equations efficiently. These settings collectively enable accurate simulation of plastic deformation and ensure stable convergence during the nonlinear analysis.

2.8. Evaluation Parameters

The mechanical behavior of the damper is evaluated through several key parameters, including equivalent stress (von Mises stress), total deformation, equivalent plastic strain (PEEQ), and reaction force. The equivalent stress is used to identify stress distribution and potential yielding regions within the damper, while total deformation provides insight into the overall displacement and flexibility of the structure. The equivalent plastic strain (PEEQ) is employed to assess the extent of plastic deformation and the energy dissipation capability of the damper. In addition, the reaction force is analyzed to determine the load-carrying capacity and stiffness characteristics of the system.

To further investigate the influence of design variables on the damper performance, a parametric study is conducted focusing on both geometric and material variations. In the first stage, the effect of plate thickness is evaluated by varying the thickness into four configurations, namely 15 mm, 20 mm, 25 mm, and 30 mm, using structural steel as the reference material. In the second stage, the influence of material properties is examined by comparing three different materials structural steel, grey cast iron, and aluminum alloy using the baseline thickness of 20 mm. The results obtained from these analyses are systematically compared to identify the effects of thickness and material variation on the mechanical performance of the damper, particularly in terms of strength, deformation, and plastic behavior.

3. RESULT AND DISCUSSION

3.1. Effect of Plate Thickness on Deformation Behavior

The effect of plate thickness on the deformation behavior of the mild steel damper is illustrated in Figure 6 which presents the variation of total deformation along the Y-axis for different thickness configurations (15 mm, 20 mm, 25 mm, and 30 mm). It can be observed that deformation increases progressively along the Y-axis for all models, indicating that the maximum displacement occurs at the upper region of the damper, while the lower region remains relatively constrained due to the applied boundary conditions.

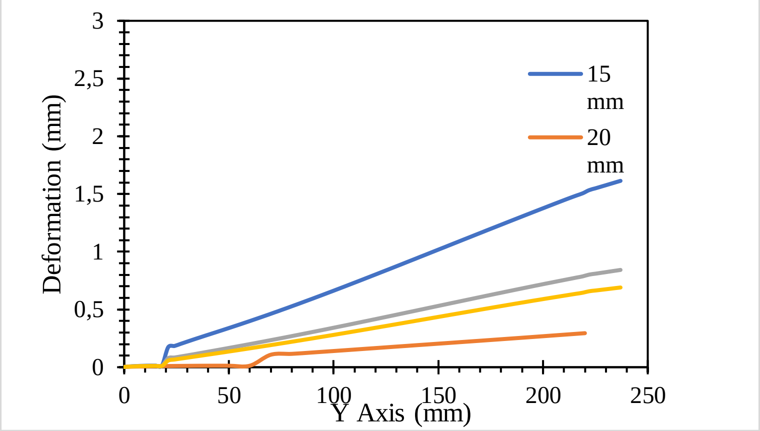


Figure 6 Total deformation along the Y-axis for different plate thicknesses

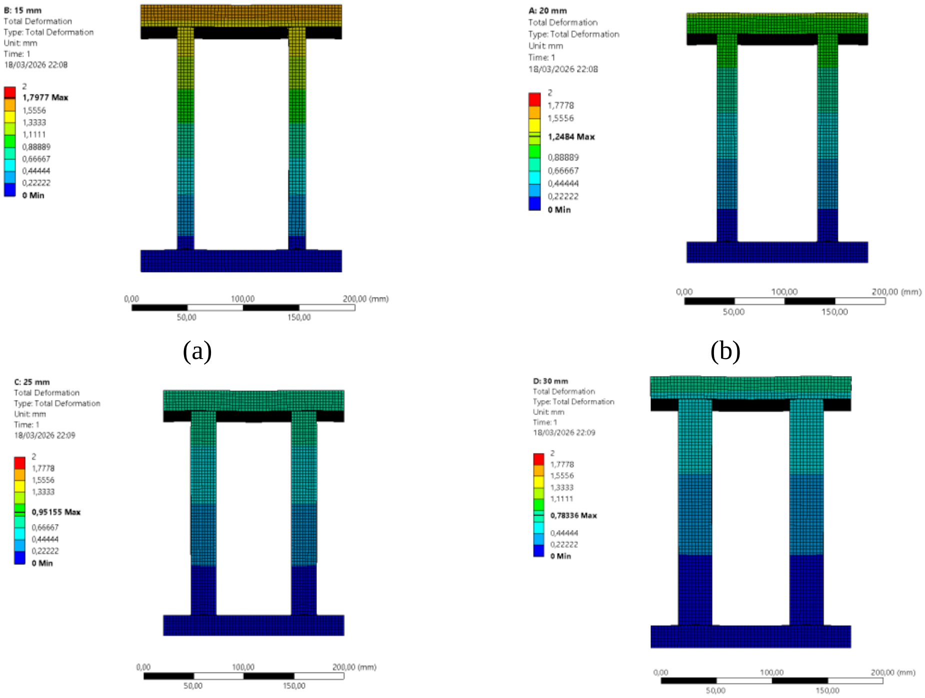
A significant influence of plate thickness on deformation behavior is clearly evident. The 15 mm configuration exhibits the highest deformation, reaching approximately 1.6 mm at the maximum Y-axis position. In contrast, the 20 mm model shows a substantially lower deformation, followed by the 25 mm and 30 mm configurations, which demonstrate moderate deformation levels. This trend indicates that increasing plate thickness enhances the structural stiffness of the damper, thereby reducing its deformation under identical loading conditions.

This behavior can be attributed to the increase in cross-sectional area and moment of inertia associated with greater plate thickness. According to fundamental structural mechanics, the bending stiffness of a structural component is governed by the product of the elastic modulus and the area moment of inertia (EI), where the moment of inertia increases significantly with thickness, leading to higher resistance to bending deformation [29]. A thicker plate therefore provides greater resistance to both bending and shear deformation, resulting in a stiffer structural response. Conversely, thinner plates possess lower stiffness, leading to larger deformation under the same applied load.

This trend is consistent with previous numerical and experimental studies, which reported that increasing plate thickness enhances stiffness and reduces deformation due to improved load-carrying capacity and structural rigidity [30].

The deformation contour results further support these findings. Figure 7 presents the deformation contours of the mild steel damper for different plate thicknesses, namely (a) 15 mm, (b) 20 mm, (c) 25 mm, and (d) 30 mm. As shown in the figure, the deformation is primarily concentrated in the web region of the damper, indicating that this area acts as the main energy dissipation zone under the applied loading conditions. For the 15 mm configuration, the contour plot shows a wider distribution of higher deformation (yellow to red regions), particularly in the upper flange and web regions, indicating significant bending and shear effects. In contrast, the 30 mm configuration exhibits a more uniform deformation distribution with lower magnitude (predominantly blue to green regions), reflecting a stiffer response and improved load distribution.

The intermediate thickness configurations (20 mm and 25 mm) exhibit deformation characteristics between these two extremes. The 20 mm model demonstrates relatively low deformation while maintaining a certain degree of flexibility, whereas the 25 mm model provides a balanced response between stiffness and deformation control. This suggests that intermediate thickness values may offer an optimal compromise between structural rigidity and deformation capacity.



(a) (b)

(c) (d)

Figure 7 Deformation contours of the mild steel damper for (a) 15 mm, (b) 20 mm, (c) 25 mm, and (d) 30 mm thickness.

From an engineering perspective, these results highlight a trade-off between stiffness and deformability. In structural mechanics, increasing plate thickness leads to higher flexural rigidity (EI), thereby enhancing stiffness and reducing deformation; however, excessive stiffness may limit the ability of the damper to undergo controlled plastic deformation, which is essential for effective energy dissipation. Previous studies on metallic dampers have shown that optimal damper performance is achieved through a balance between stiffness and ductility, where sufficient deformation capacity is required to absorb and dissipate energy under loading conditions. For instance, Li et al. [7] and Wang et al. [10] reported that increasing geometric stiffness improves structural stability but may reduce energy dissipation efficiency if deformation is overly restricted.

Therefore, selecting an appropriate plate thickness is essential to achieve optimal mechanical performance. Based on the present results, the thickness range of 20 mm to 25 mm appears to provide a favorable balance between stiffness and deformation behavior, which is consistent with previous findings indicating that intermediate geometric configurations offer optimal performance in metallic damping systems.

3.2. Effect of Plate Thickness on Stress Distribution

The influence of plate thickness on the stress distribution of the mild steel damper is presented in Fig. 7, which illustrates the variation of equivalent (von Mises) stress along the Y-axis for different thickness configurations (15 mm, 20 mm, 25 mm, and 30 mm). It is observed that all models exhibit a similar stress distribution pattern, characterized by a sharp increase in stress near the lower region, followed by a gradual decrease along the height of the damper, and a secondary stress concentration near the upper region.

Among all configurations, the 15 mm model exhibits the highest stress concentration, reaching values exceeding 1000 MPa near the lower section of the damper. This significant difference compared to the other thickness configurations can be explained by fundamental stress–area relationships, where stress is inversely proportional to the effective load-bearing area. Thinner plates possess smaller cross-sectional area and lower section modulus, resulting in reduced capacity to distribute internal forces and consequently higher localized stress concentrations. In addition, lower stiffness in thinner plates leads to greater deformation, which further amplifies stress concentration in critical regions.

In contrast, increasing the plate thickness leads to a substantial reduction in stress magnitude due to the increase in load-carrying capacity and improved stress redistribution. The 20 mm configuration shows a noticeable decrease in peak stress, while the 25 mm and 30 mm models exhibit further reductions with more uniform stress distribution. This trend is consistent with previous studies, which reported that increasing structural thickness significantly reduces stress concentration and enhances structural stability by improving section properties and stiffness [8][10]. These findings confirm that plate thickness plays a critical role in controlling stress concentration in metallic damper systems.

This trend can be explained by the relationship between stress and cross-sectional properties. As the plate thickness increases, the effective load-bearing area becomes larger, resulting in a reduction of stress under the same applied load. Additionally, the increased stiffness of thicker plates contributes to a more uniform stress distribution, thereby minimizing localized stress concentrations.

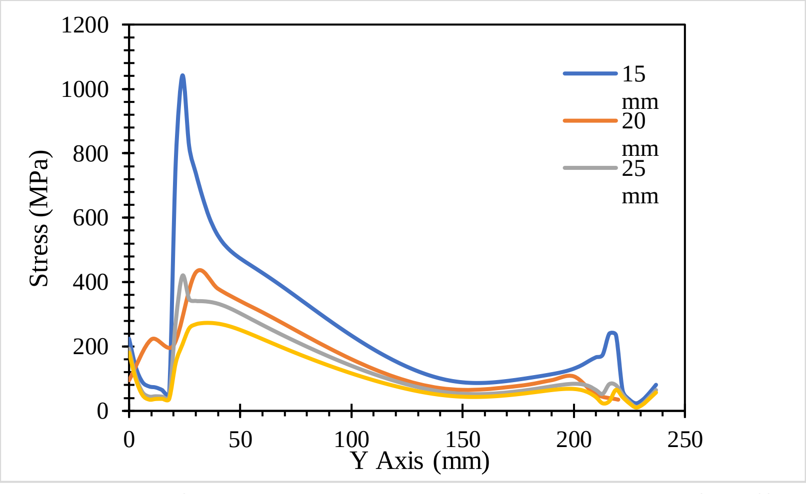


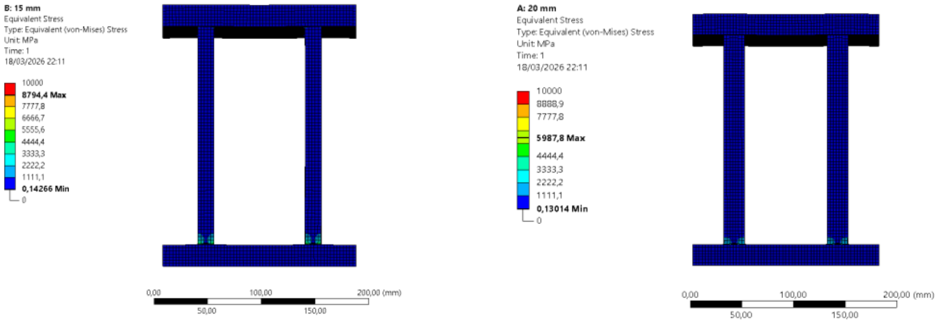
Figure 8 Distribution of equivalent (von Mises) stress along the Y-axis for different plate thicknesses.

The stress contour plots shown in Figure 9 provide further insight into the distribution characteristics of the damper under quasi-static loading conditions. As illustrated in the figure, for the 15 mm configuration, high stress concentrations (yellow to red regions) are clearly observed near the connection between the web and the base plate. This region acts as a critical zone where stress localization occurs due to geometric discontinuity and load transfer mechanisms, making it highly susceptible to yielding or failure initiation.

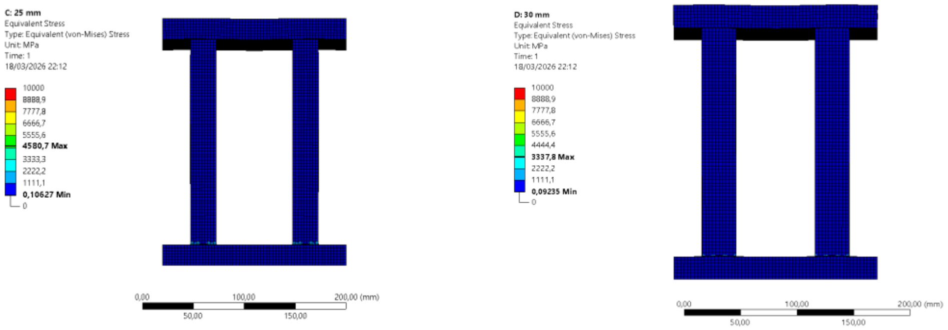
The significantly higher stress observed in the 15 mm model compared to other configurations can be explained by fundamental stress distribution theory, where stress is inversely proportional to the cross-sectional area and section modulus. Thinner plates possess lower stiffness and reduced load-carrying capacity, leading to greater deformation and amplified stress concentration in critical regions. Similar behavior has been reported in previous studies on metallic dampers and steel structures, where reduced thickness results in higher localized stress and earlier yielding [10].

In contrast, the 30 mm configuration shows significantly reduced stress intensity, with most regions dominated by lower stress levels (blue to green), indicating a more stable structural response. The increased thickness enhances the moment of inertia and structural stiffness, allowing more uniform stress redistribution across the damper. The intermediate thickness configurations (20 mm and 25 mm) demonstrate a gradual transition between these two extremes. The 20 mm model still shows noticeable stress concentration, although significantly lower than the 15 mm model, while the 25 mm model exhibits improved stress distribution with reduced peak values. This trend is consistent with previous findings that increasing structural thickness improves stress distribution and reduces peak stress due to enhanced stiffness and section properties [8].

From an engineering standpoint, these results highlight the critical role of plate thickness in controlling stress concentration and structural performance. While thinner plates may provide greater flexibility, they are more susceptible to high stress concentration and potential failure. Conversely, thicker plates enhance load-carrying capacity and reduce stress levels but may increase structural stiffness excessively, potentially limiting energy dissipation capability. Therefore, an optimal thickness should be selected to balance stress reduction and deformation capacity. Based on the present findings, the thickness range of 20 mm to 25 mm appears to provide a favorable compromise between stress control and structural efficiency, particularly for quasi-static loading conditions relevant to damper applications.



(a) (b)



(c) (d)

Figure 9 Stress contour of mild steel damper with (a) 15 mm, (b) 20 mm, (c) 25 mm, and (d) 30 mm thickness.

3.3 Effect of Plate Thickness on Strain Distribution

The effect of plate thickness on the strain distribution of the mild steel damper is presented in Fig. 9, which illustrates the variation of equivalent strain along the Y-axis for different thickness configurations (15 mm, 20 mm, 25 mm, and 30 mm). Similar to the stress distribution, all models exhibit a consistent pattern characterized by a pronounced strain concentration near the lower region of the damper, followed by a gradual decrease along the height, and a minor increase near the upper region.

Among all configurations, the 15 mm model exhibits the highest strain values, with a peak reaching approximately 0.009. This indicates that thinner plates undergo significantly larger deformation at the material level, resulting in higher strain accumulation. In contrast, increasing the plate thickness leads to a substantial reduction in strain magnitude. The 20 mm configuration shows a considerable decrease in peak strain, while the 25 mm and 30 mm models exhibit further reductions, with relatively low and more stable strain levels.

This behavior can be attributed to the increased stiffness and load distribution capacity associated with thicker plates. From the perspective of structural mechanics, stiffness is governed by flexural rigidity (EI), where the moment of inertia increases significantly with plate thickness, thereby enhancing resistance to deformation. As the plate thickness increases, the applied load is distributed over a larger cross-sectional area and section modulus, which reduces localized deformation and strain concentration. Conversely, thinner plates exhibit lower stiffness and reduced resistance to deformation, resulting in higher strain under the same loading conditions.

This observation is consistent with previous studies. For instance, experimental results under quasi-static and cyclic loading have shown that structural components with higher stiffness exhibit improved load distribution and reduced deformation concentration [31]. In addition, studies on steel–concrete composite structures indicate that increasing steel plate thickness significantly enhances stiffness and load-carrying capacity, while reducing strain localization and improving structural stability [32]. These findings support the present results, confirming that plate thickness plays a critical role in controlling strain behavior and structural response.

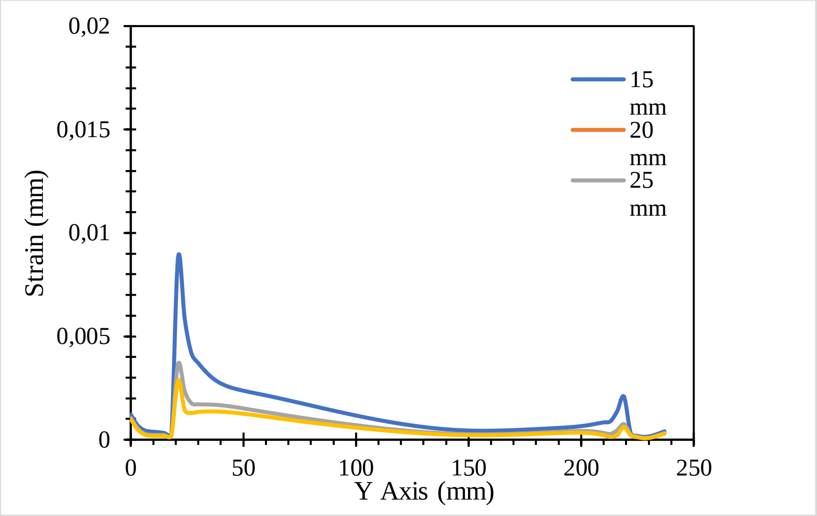


Figure 10 Distribution of equivalent strain along the Y-axis for different plate thicknesses.

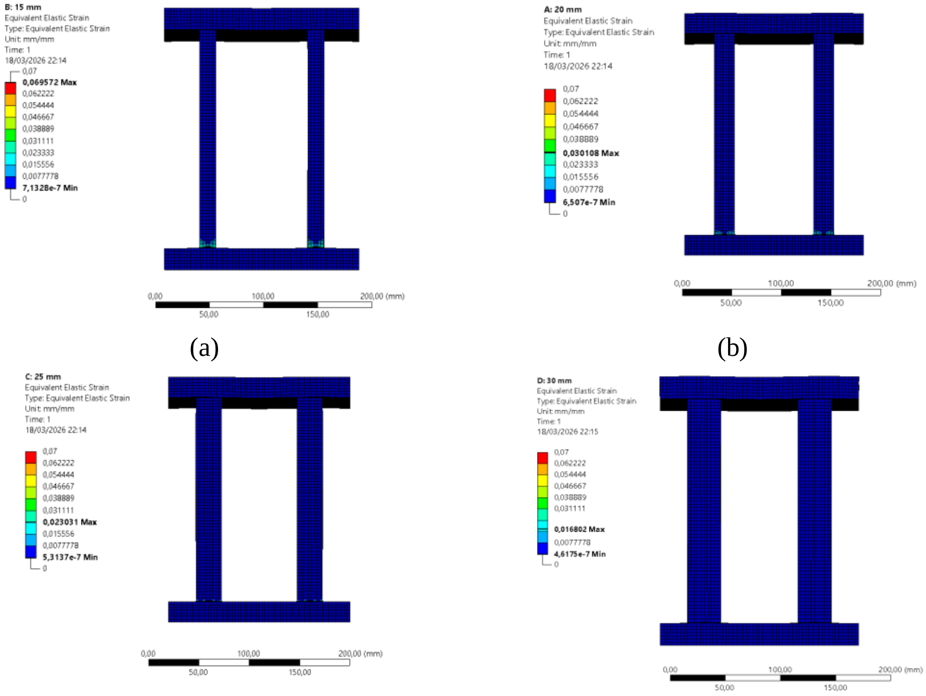
The strain contour plots shown in Figure 11 provide additional insight into the deformation mechanism of the damper under quasi-static loading conditions. As illustrated in the figure, for the 15 mm configuration, high strain concentrations (green to yellow regions) are clearly observed near the junction between the web and the base plate. This region represents a critical zone where plastic deformation is likely to initiate due to stress localization and geometric discontinuity. The significantly higher strain observed in the 15 mm model compared to other configurations is attributed to its lower stiffness and reduced load-carrying capacity, which leads to greater deformation under the same loading conditions.

This behavior is consistent with structural mechanics principles, where strain is directly related to stress and inversely related to stiffness. Thinner plates tend to experience higher strain localization due to limited resistance to deformation. Previous studies have also shown that under quasi-static and cyclic loading, structural components with lower stiffness exhibit higher strain concentration and earlier plastic deformation [31].

In contrast, the 30 mm configuration shows a predominantly low strain distribution (blue regions), indicating that the structure remains largely within the elastic or near-elastic range. The increased thickness enhances the moment of inertia and stiffness, allowing the applied load to be distributed more uniformly across the structure. Similar findings have been reported in steel–concrete composite systems, where increasing plate thickness improves stiffness and reduces strain localization, resulting in a more stable structural response [32].

The intermediate thickness configurations (20 mm and 25 mm) demonstrate a gradual transition in strain behavior. The 20 mm model still shows noticeable strain concentration, although significantly lower than the 15 mm model, while the 25 mm model exhibits improved strain distribution with reduced peak values. This gradual transition indicates that increasing thickness not only reduces the magnitude of strain but also enhances its distribution across the structure.

From an engineering perspective, strain behavior is a critical indicator of energy dissipation capability in damper systems. Higher strain levels, as observed in thinner plates, indicate greater deformation capacity and potential energy absorption; however, excessive strain may lead to premature yielding or localized failure. On the other hand, thicker plates exhibit lower strain, indicating higher stiffness but reduced energy dissipation potential. Therefore, an optimal plate thickness should balance strength and ductility. Based on the present results, the thickness range of 20 mm to 25 mm provides a favorable balance between controlled deformation and structural stability under quasi-static loading conditions.



(a) (b)

(c) (d)

Figure 11 Strain contour of mild steel damper with (a) 15 mm, (b) 20 mm, (c) 25 mm, and (d) 30 mm thickness

Overall, the results clearly demonstrate that plate thickness plays a critical role in governing the mechanical performance of the mild steel damper. Increasing plate thickness significantly enhances structural stiffness, which leads to reduced deformation, lower equivalent plastic strain, and a more uniform stress distribution. This behavior is primarily attributed to the increase in bending rigidity (EI), where stiffness is proportional to the cube of thickness, resulting in a substantial improvement in load-carrying capacity. Similar findings have been reported in previous studies on metallic dampers, where thicker sections reduce stress concentration and improve structural stability.

However, excessive thickness may adversely affect the damper performance by limiting its ability to undergo controlled plastic deformation, which is essential for energy dissipation in structural applications. In this context, thinner configurations (e.g., 15 mm) exhibit higher deformation and strain, indicating greater energy dissipation potential but also a higher risk of instability and localized failure. Conversely, thicker configurations (e.g., 30 mm) provide superior strength and stiffness but reduce ductility and deformation capacity. Therefore, an optimal thickness range is required to achieve a balance between stiffness and ductility. Based on the present results, the thickness range of 20–25 mm provides the most favorable performance, offering sufficient structural rigidity while maintaining adequate deformation capacity for effective energy dissipation.

3.4 Effect of Material Variation on Deformation Behavior

The effect of material variation on the deformation behavior of the damper is illustrated in Figure 12, which presents the distribution of total deformation along the Y-axis for structural steel, grey cast iron, and aluminum. All material configurations exhibit a consistent trend, where deformation increases progressively along the Y-axis, with the maximum displacement occurring at the upper region of the damper due to the applied loading and boundary constraints.

A clear distinction in deformation magnitude is observed among the three materials. Aluminum exhibits the highest deformation, reaching approximately 0.85 mm at the maximum Y-axis position. This is followed by grey cast iron, which shows moderate deformation of around 0.5 mm. In contrast, structural steel demonstrates the lowest deformation, with a maximum value of approximately 0.3 mm. These results indicate that material stiffness plays a dominant role in controlling structural deformation.

The observed behavior can be explained by differences in Young’s modulus among the materials. Young’s modulus is a fundamental mechanical property that represents the stiffness of a material and its resistance to elastic deformation under applied load. According to elasticity theory, a higher Young’s modulus indicates greater resistance to deformation, as strain is directly proportional to stress and inversely proportional to the modulus of elasticity .

Structural steel, having the highest modulus of elasticity, therefore provides greater resistance to deformation, resulting in a stiffer structural response. In contrast, aluminum, with a significantly lower Young’s modulus, exhibits higher deformation due to its reduced stiffness. This behavior has been widely reported in experimental and numerical studies, where materials with lower elastic modulus show increased deformation under identical loading conditions [33].

Grey cast iron shows intermediate behavior, with deformation values lying between those of steel and aluminum, reflecting its moderate stiffness. Similar trends have been observed in comparative studies of metallic materials, where stiffness differences governed by elastic modulus significantly influence deformation response and structural performance [34].

Additionally, a noticeable change in the deformation curve is observed around the mid-height region (approximately 50–70 mm along the Y-axis), particularly for aluminum and grey cast iron. This indicates a localized change in stiffness, which may be associated with stress redistribution or the onset of nonlinear deformation behavior. Structural steel, however, maintains a smoother and more gradual deformation profile, suggesting a more stable structural response.

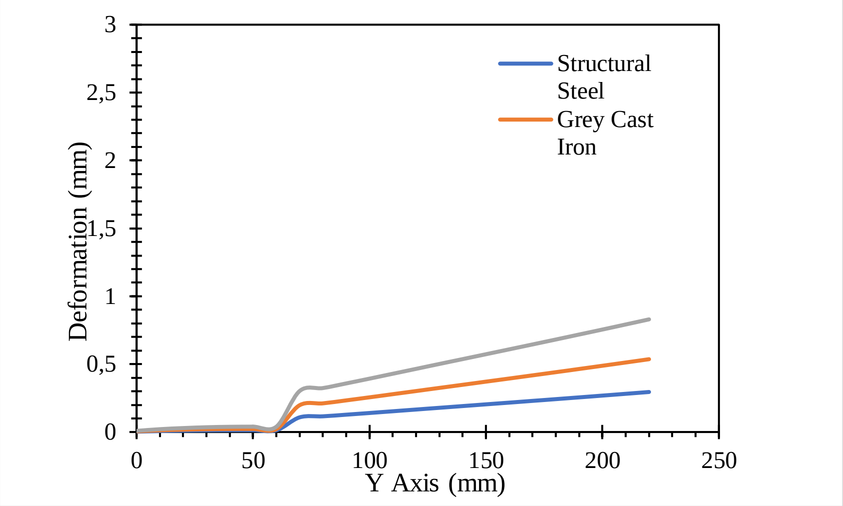


Figure 12 Total deformation along the Y-axis for different material types

From an engineering perspective, these results highlight the importance of material selection in controlling deformation behavior. In material mechanics, deformation response is strongly governed by elastic modulus and ductility, where materials with higher stiffness exhibit lower deformation under the same loading conditions, while ductile materials can sustain larger strains before failure. Previous studies have shown that structural steel possesses a high modulus of elasticity combined with good ductility, enabling it to provide both stiffness and stable deformation behavior under loading conditions [32]. Therefore, structural steel is highly suitable for applications requiring minimal displacement and high structural stability.

In contrast, aluminum alloys, which have significantly lower stiffness, tend to exhibit higher deformation under identical loading conditions. This behavior has been widely reported in comparative material studies, where aluminum structures demonstrate greater flexibility due to their lower elastic modulus, making them suitable for applications where weight reduction and flexibility are prioritized [31].

Grey cast iron shows moderate deformation behavior due to its intermediate stiffness; however, its brittle nature, characterized by low tensile strength and limited plastic deformation capacity, may restrict its application in energy dissipation systems. It has been reported that brittle materials are more prone to sudden failure without significant prior deformation, which reduces their effectiveness in applications requiring ductility and energy absorption [32]. These findings are consistent with the present results, confirming that material selection plays a crucial role in balancing stiffness, deformation capacity, and structural reliability.

3.5 Effect of Material Variation on Stress Distribution

The effect of material variation on the stress distribution of the damper is presented in Figure 13, which shows the variation of equivalent (von Mises) stress along the Y-axis for structural steel, grey cast iron, and aluminum. All material configurations exhibit a similar overall trend, characterized by localized stress concentrations near the lower and mid-height regions, followed by a gradual reduction in stress toward the upper section of the damper.

A significant difference in stress magnitude and distribution is observed among the three materials. Grey cast iron and aluminum exhibit the highest peak stress values, reaching approximately 620

MPa in the mid-region (around 60–80 mm along the Y-axis). In contrast, structural steel shows a lower peak stress of approximately 430 MPa, occurring closer to the lower section of the damper.

The higher stress observed in aluminum and grey cast iron can be attributed to their lower stiffness and reduced ability to redistribute internal forces effectively compared to structural steel. As a result, stress becomes more concentrated in specific regions, particularly around geometric discontinuities such as the junction between the web and flange. In contrast, structural steel demonstrates a more gradual stress distribution, indicating a more uniform load transfer and better structural integrity.

Furthermore, the stress distribution along the damper height, as illustrated in Figure 10, is evaluated under quasi-static loading conditions. Structural steel exhibits a noticeable reduction in stress along the height, reaching relatively low values in the mid-to-upper regions before slightly increasing again near the top. This behavior indicates effective stress redistribution, which is primarily attributed to the ductile nature of structural steel and its high capacity for plastic deformation. In nonlinear structural systems, ductile materials allow stress to be redistributed from highly stressed regions to surrounding areas through plastic yielding, thereby reducing stress concentration and improving overall structural stability. Similar behavior has been observed in modular steel structures subjected to nonlinear static (pushover) analysis, where material nonlinearity contributes to stress redistribution and deformation control [35].

In contrast, aluminum and grey cast iron maintain relatively higher stress levels over a larger portion of the structure, as shown in the contour plots. This indicates less efficient stress redistribution, which can be attributed to their lower stiffness (in the case of aluminum) and limited ductility (in the case of grey cast iron). As discussed in nonlinear structural studies, materials with limited ductility exhibit reduced ability to redistribute stresses, leading to higher stress concentration and increased risk of localized failure [36].

From an engineering standpoint, these results highlight the importance of material ductility in controlling stress distribution and preventing localized failure. Materials with higher ductility, such as structural steel, are more capable of redistributing stress and delaying failure, whereas materials with lower ductility are more susceptible to stress concentration and premature fracture. This behavior is particularly critical in structural systems subjected to lateral loading, where nonlinear response and stress redistribution govern overall performance.

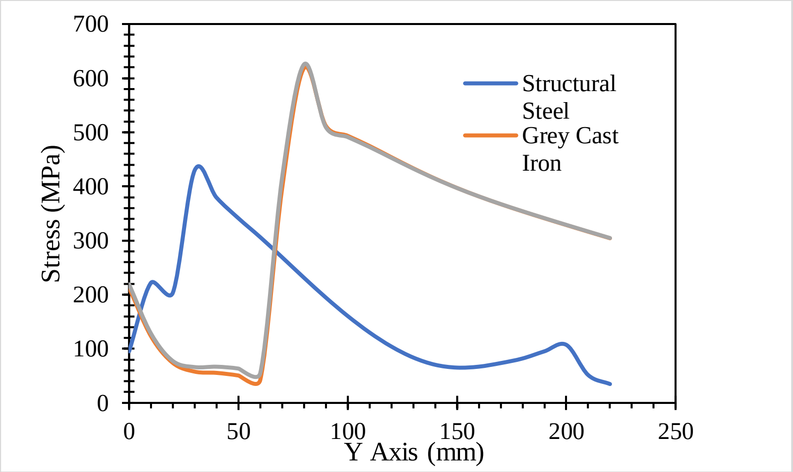


Figure 13 Distribution of equivalent (von Mises) stress along the Y-axis for different material types

From the stress contour perspective (as supported by simulation results), high stress concentrations for aluminum and grey cast iron are expected to be more localized and intense, which may increase the risk of material failure, especially for grey cast iron due to its brittle nature. Structural steel, with its lower peak stress and smoother distribution, provides a more reliable and stable performance under loading.

From an engineering standpoint, these results highlight that structural steel is the most favorable material in terms of stress performance, as it minimizes peak stress and promotes a more uniform stress distribution. This behavior is strongly associated with the inherent ductility and strain-hardening capability of steel, which allow effective stress redistribution and the formation of stable plastic zones under loading conditions [37]. Previous studies on metallic dampers have demonstrated that ductile steel materials are capable of sustaining significant plastic deformation while maintaining stable mechanical behavior, thereby reducing stress concentration and improving structural reliability [38].

In contrast, aluminum, although advantageous in terms of lightweight properties, tends to exhibit higher stress concentration due to its lower modulus of elasticity and limited capacity to redistribute internal forces. This leads to more localized deformation and increased susceptibility to yielding, particularly under repeated or high loading conditions, as reported in studies on aluminum alloys where lower fatigue strength and continuous stress accumulation were observed.

Grey cast iron, despite showing stress levels comparable to aluminum, is less desirable due to its brittle nature and limited ductility. Brittle materials are unable to effectively redistribute stress, resulting in localized stress concentration and a higher risk of sudden failure. This phenomenon has been widely reported in damper studies, where stress concentration in brittle regions leads to premature cracking and failure initiation [39]. Therefore, the superior performance of structural steel can be attributed to its combined strength, ductility, and ability to undergo controlled plastic deformation, making it a more reliable material for energy dissipation and structural applications.

Overall, the results demonstrate that material selection significantly influences stress distribution, with structural steel offering the most efficient and reliable performance for damper applications.

3.6 Effect of Material Variation on Strain Distribution

The effect of material variation on the strain distribution of the damper is presented in Figure 14, which illustrates the variation of equivalent strain along the Y-axis for structural steel, grey cast iron, and aluminum. All materials exhibit a similar general trend, characterized by localized strain concentrations in specific regions, particularly near the lower and mid-height sections of the damper, followed by relatively low strain levels along the remaining length.

A significant difference in strain magnitude is observed among the materials. Aluminum exhibits the highest strain values, reaching a peak of approximately 0.015, indicating a high level of deformation at the material level. Grey cast iron shows moderate strain values, with a peak around 0.01, while structural steel demonstrates the lowest strain, with a maximum value of approximately 0.0035. These results clearly indicate that material ductility and stiffness strongly influence strain behavior.

The high strain observed in aluminum can be attributed to its relatively low Young’s modulus and yield strength, which allow larger deformation under the same loading conditions. This behavior is consistent with fundamental mechanics principles, where materials with lower stiffness exhibit higher strain under identical stress levels. Previous studies have reported that aluminum alloys tend to experience higher strain accumulation and more extensive plastic deformation due to their lower elastic modulus compared to structural steel (Huang et al., 2019; Ma et al., 2021).

However, excessive strain may lead to instability or premature failure if not properly controlled, particularly due to localized plastic deformation and reduced load redistribution capability. In contrast, structural steel exhibits lower strain due to its higher stiffness and yield strength, resulting in a more controlled and stable deformation response. This behavior is strongly supported by studies on steel dampers, which demonstrate that ductile steel materials can effectively redistribute stress and strain through stable plastic deformation and strain-hardening mechanisms, thereby reducing strain concentration [40].

Grey cast iron, although showing moderate strain levels, exhibits fundamentally different behavior compared to ductile materials. Its strain distribution appears more localized and less uniform, indicating limited capacity for plastic deformation. This phenomenon is associated with its brittle microstructure, where graphite flakes act as internal stress concentrators, leading to localized deformation and early crack initiation. Similar observations have been reported in studies of brittle metallic materials, where limited ductility restricts strain distribution and promotes sudden failure under loading [41].

The strain contour results further support these observations. Aluminum shows wider regions of higher strain distribution, indicating extensive plastic deformation, while structural steel exhibits more uniform and controlled strain distribution, reflecting efficient energy dissipation without excessive deformation. In contrast, grey cast iron shows localized strain concentrations that may act as critical points for crack initiation and propagation. Such behavior has been widely reported in numerical and experimental investigations of brittle materials, where strain localization governs failure mechanisms [42].

It should be noted that the present analysis is conducted under static monotonic loading conditions, which primarily capture the initial nonlinear and plastic deformation behavior. Under cyclic or seismic loading conditions, these differences are expected to become more significant, particularly in terms of energy dissipation and fatigue resistance.

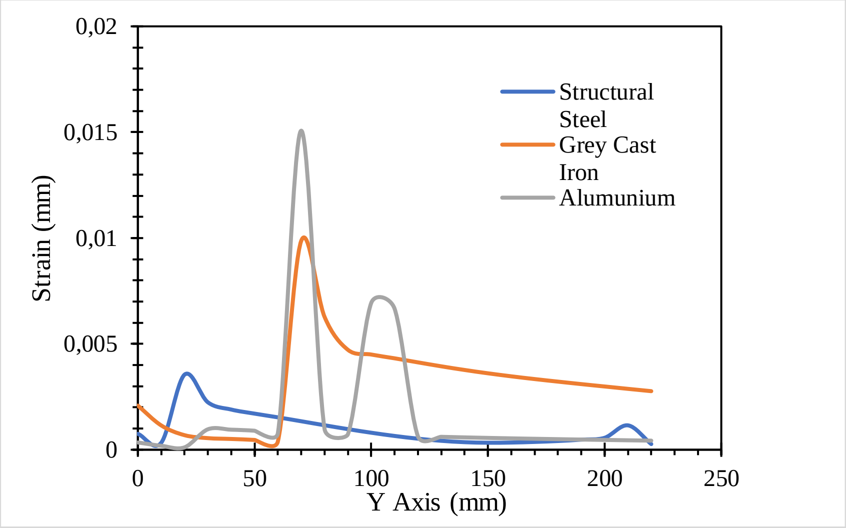


Figure 14 Distribution of equivalent strain along the Y-axis for different material types

From an engineering perspective, strain behavior is closely related to the energy dissipation capability of dampers. Materials with higher strain capacity, such as aluminum, can absorb more energy but may suffer from excessive deformation. Structural steel offers a balanced response, with sufficient ductility to dissipate energy while maintaining structural integrity. Grey cast iron, due to its limited ductility, is less suitable for applications requiring reliable energy dissipation.

The results clearly indicate that material selection plays a fundamental role in determining the mechanical performance of the mild steel damper, particularly in balancing stiffness, strength, and ductility. Structural steel exhibits the most stable and reliable behavior, characterized by lower deformation, reduced stress concentration, and more uniform strain distribution. This performance is primarily attributed to its high stiffness and ductile nature, which enable effective stress redistribution and stable plastic deformation. Similar behavior has been widely reported in metallic damper studies, where structural steel provides superior energy dissipation performance due to its strain-hardening capability. In contrast, aluminum demonstrates higher deformability and strain capacity due to its lower Young’s modulus and yield strength. This allows aluminum to undergo larger plastic deformation and potentially absorb more energy. However, this advantage is accompanied by increased deformation and strain concentration, which may lead to instability and reduced structural reliability under loading conditions.

Grey cast iron, on the other hand, exhibits less favorable performance due to its limited ductility and brittle characteristics. The presence of graphite flakes in its microstructure acts as stress concentrators, leading to localized strain accumulation and increasing the likelihood of crack initiation and sudden failure. As a result, its ability to redistribute stress and sustain plastic deformation is significantly lower compared to ductile materials. Therefore, the selection of material must consider the trade-off between strength, ductility, and energy dissipation capability. Based on the present findings, structural steel is the most suitable material for damper applications, as it provides an optimal combination of stiffness, controlled deformation, and reliable mechanical performance.

The combined analysis highlights that an optimal damper design requires a careful balance between geometric stiffness and material ductility. A plate thickness in the range of 20–25 mm, combined with structural steel material, provides the most favorable performance by ensuring adequate stiffness while maintaining sufficient deformation capacity for energy dissipation. From an engineering perspective, this balance is critical in preventing undesirable structural failure modes.

Excessively thin plates (e.g., 15 mm) tend to experience high strain localization and elevated stress concentration, which may trigger early yielding followed by instability phenomena such as local buckling or low-cycle fatigue failure under repeated loading conditions. On the other hand, excessively thick plates (e.g., 30 mm) significantly increase stiffness but may suppress plastic deformation, thereby reducing the damper’s ability to dissipate energy and potentially shifting the failure mechanism from ductile yielding to brittle or sudden failure in adjacent structural components. Similar observations have been reported in studies on metallic dampers, where insufficient ductility or excessive stiffness can lead to unfavorable failure modes and reduced seismic performance [3][5].

In terms of material behavior, structural steel provides a stable failure mechanism characterized by distributed plastic deformation and gradual yielding, which is highly desirable in seismic-resistant design. In contrast, materials with limited ductility, such as grey cast iron, are prone to brittle fracture due to strain localization and crack initiation at stress concentration regions. Aluminum, while capable of large deformation, may suffer from excessive strain accumulation and reduced fatigue resistance, which can accelerate damage evolution under cyclic loading conditions [15].

Therefore, the engineering implementation of mild steel dampers should not only consider strength and stiffness but also the dominant failure mechanisms associated with different geometric and material configurations. The present findings suggest that selecting an appropriate thickness–material combination can effectively control deformation patterns, delay crack initiation, and ensure a ductile and stable failure mode. This provides a valuable opportunity for further development, particularly in optimizing damper design for enhanced seismic resilience, fatigue resistance, and long-term structural reliability under cyclic or dynamic loading conditions.

4. CONCLUSION

This study presents a numerical investigation of the effects of plate thickness and material variation on the mechanical behavior of an H-type mild steel damper using nonlinear finite element analysis. Based on the simulation results, several important conclusions can be drawn.

First, plate thickness has a significant influence on the structural response of the damper. Increasing the thickness from 15 mm to 30 mm leads to a substantial reduction in deformation and strain, along with a more uniform stress distribution. Thinner plates exhibit higher deformation and strain, indicating greater flexibility and energy dissipation potential, but also a higher risk of excessive deformation and localized failure. Conversely, thicker plates provide higher stiffness and load-carrying capacity but reduce the deformation capability of the damper.

Second, material properties play a crucial role in determining damper performance. Structural steel demonstrates the most favorable behavior, characterized by low deformation, reduced stress concentration, and controlled strain distribution, making it the most suitable material for damper applications. Aluminum shows higher deformation and strain due to its lower stiffness, indicating a greater capacity for energy absorption but reduced structural stability. Grey cast iron exhibits less desirable performance due to its limited ductility and tendency toward localized stress and strain concentration, which may lead to brittle failure.

Third, the interaction between thickness and material highlights the importance of achieving a balance between stiffness and ductility in damper design. An optimal configuration is identified within the thickness range of 20–25 mm using structural steel, which provides a balanced performance in terms of strength, deformation control, and energy dissipation capability.

Overall, the findings of this study provide valuable insights into the design and optimization of mild steel dampers for structural applications, particularly in seismic-resistant systems. The results emphasize that both geometric and material parameters must be carefully selected to achieve an effective balance between structural stability and energy dissipation performance. Future work is recommended to extend this study through experimental validation and dynamic loading analysis to further evaluate the damper performance under realistic seismic conditions.

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