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Numerical Analysis of the Effect of Thread Geometry on the Seismic Behavior of Bolted Connections under Near-Fault Earthquakes

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Abstract

Bolted connections are critical components in steel structures, and their performance under near-fault earthquake loading is of great importance. This study investigates the effect of thread geometry on the mechanical behavior of high-strength bolts subjected to dynamic seismic loads. Finite Element Analyses (FEA) were performed in ABAQUS under nonlinear conditions using three near-fault earthquake records: 1) Northridge, 2) Loma Prieta, and 3) Imperial Valley. Three thread geometries—triangular (Metric), square, and trapezoidal (ACME)—were examined for bolt diameters of 5 mm, 30 mm, and 56 mm. The results indicate that for small-diameter bolts (5 mm), triangular threads produced the lowest average von Mises stress of 365 MPa and showed approximately 18% greater stress uniformity than other thread types. For medium-diameter bolts (30 mm), square threads exhibited the best dynamic performance by reducing stress concentration by 22% and increasing pressure uniformity by up to 29% compared to triangular threads. In large-diameter bolts (56 mm), trapezoidal (ACME) threads provided superior seismic resistance, with an average von Mises stress of 480 MPa and a 31% reduction in stress fluctuation. Overall, the findings suggest that using square threads for medium-diameter bolts and trapezoidal threads for large bolts can effectively reduce stress concentration, enhance fatigue life, and improve seismic performance under near-fault earthquakes.

Keywords: Bolted connections, Thread geometry, High-strength bolts, Near-fault earthquakes, Finite element analysis, von Mises stress, Seismic performance.

1 | Introduction

Bolted connections are among the most critical components in steel structures, playing a decisive role in force transmission and maintaining structural continuity. The seismic performance of these connections—particularly under near-fault ground motions—has attracted increasing attention in earthquake and structural

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engineering due to the unique characteristics of such earthquakes, including large velocity pulses and short-duration, high-intensity energy input [1–5]. These features can induce highly nonlinear responses and severe stress concentrations in connection regions, making bolted joints especially vulnerable because of localized contact between threads and their sensitivity to pressure variations and slip.

Previous studies have demonstrated that near-fault velocity pulses can significantly amplify internal forces and deformation demands in structural systems. Alavi and Krawinkler [1] and Carlos et al. [2] reported that long-period velocity pulses in near-fault earthquakes may increase base shear and connection demands by more than 50% in flexible steel structures. Similar conclusions were reached by Zhai et al. [3], who emphasized the distinct response characteristics of structures subjected to near-fault versus far-field ground motions. These findings highlight the necessity of investigating not only global structural behavior but also the local response of critical components such as bolted connections under realistic seismic excitations.

With advances in Finite Element Analysis (FEA) and nonlinear numerical modeling, it has become possible to accurately simulate the mechanical behavior of bolted joints under complex loading conditions [6–9]. Recent research has shown that thread geometry plays a key role in stress distribution, load transfer among engaged threads, and fatigue performance of bolts. Wang et al. [5] and Wu et al. [4] demonstrated that variations in thread profile significantly affect stress concentration in the first engaged threads, which governs damage initiation. Although triangular (Metric) threads are widely used due to manufacturing simplicity, square and trapezoidal (ACME) threads have been reported to provide improved axial load transfer and reduced slip because of their lower contact angles and different force transmission mechanisms [7].

Despite these advances, most existing studies have primarily focused on static or quasi-static loading conditions, while the influence of real near-fault earthquake records on the dynamic behavior of different thread geometries has not been sufficiently addressed [8–12]. Experimental and numerical investigations by Zhang et al. [6] and Wang et al. [7] indicated that reducing the thread contact angle from 60° (Metric) to 29° (ACME) can decrease stress concentration factors by approximately 25%. Moreover, Dang et al. [8] and Ma et al. [9] emphasized the importance of bolt pretension and hole clearance in dynamic stability; however, the combined effect of thread geometry and near-fault seismic excitation remains largely unexplored.

From a numerical standpoint, Zhong et al. [13] highlighted that contact behavior between engaged threads is a governing factor in predicting local damage in bolted steel joints. More recently, Solodovnyk et al. [14] and Liu et al. [15] introduced advanced modeling frameworks incorporating hybrid simulations and Artificial Intelligence (AI) to improve the design and performance prediction of bolted connections. These developments reflect a broader research trend toward high-fidelity numerical simulations and data-driven approaches, as linear models have been shown to be insufficient for capturing the true nonlinear response of bolted joints subjected to near-fault ground motions [16–20]. Fully threaded models and multiscale finite element techniques have provided deeper insight into the role of thread geometry, local contact behavior, and energy dissipation mechanisms [21–27].

In parallel, the integration of AI and Machine Learning (ML) techniques has opened new avenues for seismic analysis and optimization of steel connections. Recent studies have demonstrated that deep learning algorithms can effectively identify complex dynamic response patterns and predict damage evolution in bolted joints under seismic loading [3, 28–31]. Coupling AI-based models with nonlinear finite element simulations has further improved prediction accuracy and enabled the development of optimized, performance-based design strategies [32–35].

A comprehensive review of the literature reveals that, despite extensive research on the seismic behavior of steel connections, quantitative and comparative analyses of different thread geometries subjected to real near-fault earthquake records remain limited. This gap is particularly critical for seismically active regions such as Iran, where optimizing the performance of bolted connections can significantly enhance structural safety. Recent findings suggest that appropriate modification of thread geometry may reduce stress concentration by up to 30% and increase energy dissipation capacity by approximately 40% [13–17].

The novelty of the present study lies in the nonlinear numerical investigation of the seismic response of three common thread geometries—triangular (Metric), square, and trapezoidal (ACME)—across three bolt diameters (5, 30, and 56 mm) under real near-fault earthquake records. Using high-fidelity finite element modeling in ABAQUS, the study evaluates von Mises stress and axial pressure distributions to provide quantitative criteria for optimal thread selection under realistic seismic conditions. By explicitly linking thread geometry, dynamic response, and near-fault ground motion characteristics, this research establishes a robust foundation for developing improved seismic design guidelines and future data-driven optimization of bolted connections in steel structures.

2 | Materials and Methods

The geometric configuration and material specifications of the bolts analyzed in this study were established based on a comparative framework with the work of Balaskas et al. [36]. In their study, two-dimensional and axisymmetric three-dimensional finite element models were developed to investigate bolts with different diameters and thread geometries, focusing on the influence of thread profile on load transfer mechanisms. Adopting this reference framework ensures consistency with validated numerical modeling approaches and allows meaningful comparison of results.

2.1 | Material Properties

In the present study, all geometric and mechanical properties of the bolts were defined in accordance with Part 10 of the Iranian National Building Regulations and the geometric model proposed by Balaskas et al. [36], in order to ensure accuracy, reproducibility, and comparability of the numerical results.

To realistically capture the behavior of high-strength steel bolts under dynamic loading, the material properties—including Young's modulus, Poisson's ratio, yield strength, ultimate tensile strength, and mass density—were incorporated into the finite element models based on the reference data reported in the aforementioned study. This material definition strategy maintains consistency with code-based design assumptions and enhances the reliability of the nonlinear numerical simulations.

The mechanical properties of the steel material used in the FEA are summarized in *Table 1*.

Table 1. Material properties of the modeled steel bolts.

Property	Symbol	Value	Unit
Young's modulus	E	200	GPa
Poisson's ratio	ν	0.3	—
Ultimate tensile strength	Fu	1000	kg/cm^2
Yield stress	Fy	900	kg/cm^2
Mass density	ϱ	7850	kg/m^3

2.2 | Thread Pitch and Bolt Diameter

Given that the present study adopts a comparative approach to evaluate the influence of thread geometry on the mechanical performance of bolted connections, three bolt diameters—5 mm, 30 mm, and 56 mm—were selected for analysis. For each diameter, the corresponding thread pitch was defined in accordance with standard geometric specifications and is summarized in *Table 2*.

Table 2. Specifications of thread pitch and bolt diameter used in the analysis.

Bolt Diameter (D)	Thread Pitch (P)	Unit
5	0.8	mm
30	3.5	mm
56	5.5	mm

2.3 | Meshing Strategy

To achieve higher numerical accuracy, the meshing procedure of the bolt models was implemented using a layered discretization scheme between the threads, allowing for a more accurate representation of force transfer across the contacting surfaces.

To improve solution convergence and reduce numerical errors, the element size was defined as a function of bolt diameter. Accordingly, the nodal spacing was set to 0.8 mm for 5 mm bolts, 2.1 mm for 30 mm bolts, and 3 mm for 56 mm bolts.

Meshing was performed independently for each bolt configuration to ensure that contact interactions and stress transmission could be evaluated separately for each model. *Fig. 1* presents the meshed geometry of a representative bolt model.

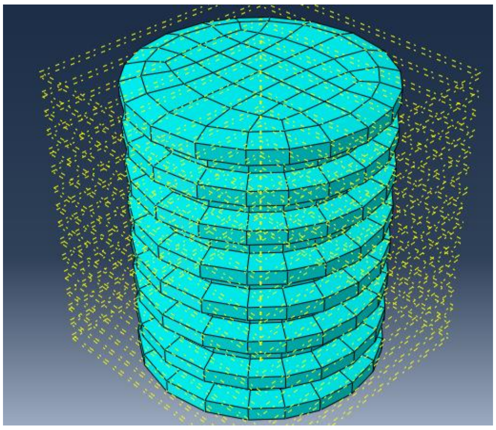


Fig. 1. Geometry of the meshed bolt model.

2.4 | Loading Conditions

In the numerical simulations, loads were applied uniformly and continuously over the entire volume of each bolt model. The magnitudes of the applied forces were defined according to *Table 3*.

To realistically represent the connection behavior, the specimen was constrained with a single translational degree of freedom along the X-axis, while one end of the bolt was subjected to an acceleration boundary condition to simulate seismic excitation.

These boundary and loading conditions enabled a precise evaluation of the dynamic response and the induced stress distribution in bolts under near-fault earthquake scenarios. *Fig. 2* depicts the overall configuration of the boundary constraints and the applied loading scheme.

Table 3. Loading parameters used in the numerical simulations.

Bolt Diameter (D)	Applied Force (N)
5	1000
30	6000
56	11200

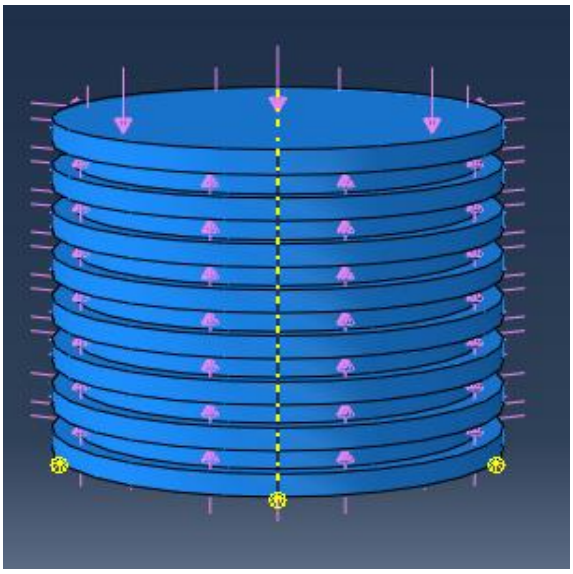


Fig. 2. Schematic representation of bolt constraints and loading.

3 | Application of Near-Fault Earthquake Records to the Bolts

To simulate dynamic seismic excitation, averaged near-fault earthquake records were applied to the bolt models. Three representative events — Northridge (1994), Loma Prieta (1989), and Imperial Valley (1979) — were selected and time-averaged to produce a consistent analysis duration of 4.6 seconds.

This averaged time-history was implemented as an acceleration input, capturing the velocity pulses and the distinct characteristics of near-fault ground motions, thereby enabling a realistic assessment of the mechanical response of bolt threads. *Fig. 3* presents the averaged near-fault earthquake records used in this study.

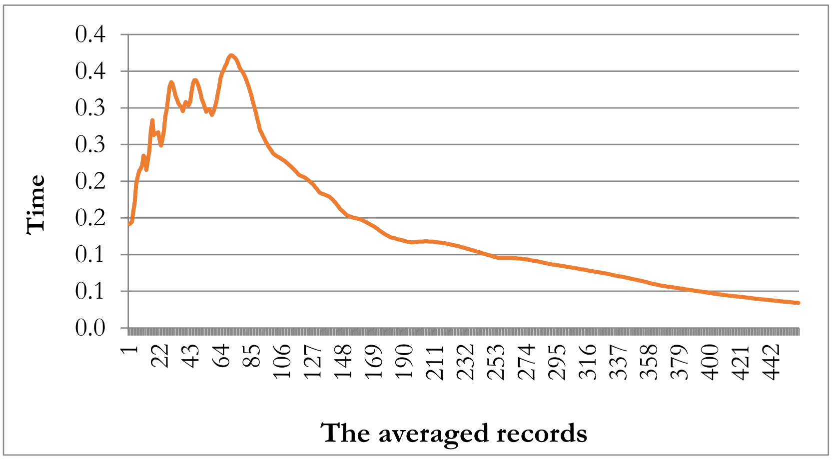


Fig. 3. Averaged records of near-fault earthquake ground motions.

4 | Analysis and Results

The von Mises stress and thread pressure distributions of bolts with triangular (Metric), trapezoidal (ACME), and square threads were analyzed for diameters of 5 mm, 30 mm, and 56 mm under forces and near-fault earthquake pulses.

Results indicate that increasing the bolt diameter reduces the load carried by the first three threads, particularly the first thread, while improving the continuity and uniformity of stress distribution along the threads. Consequently, larger bolts exhibit a more stable seismic response. The observed trends are depicted in *Figs. 4–7*.

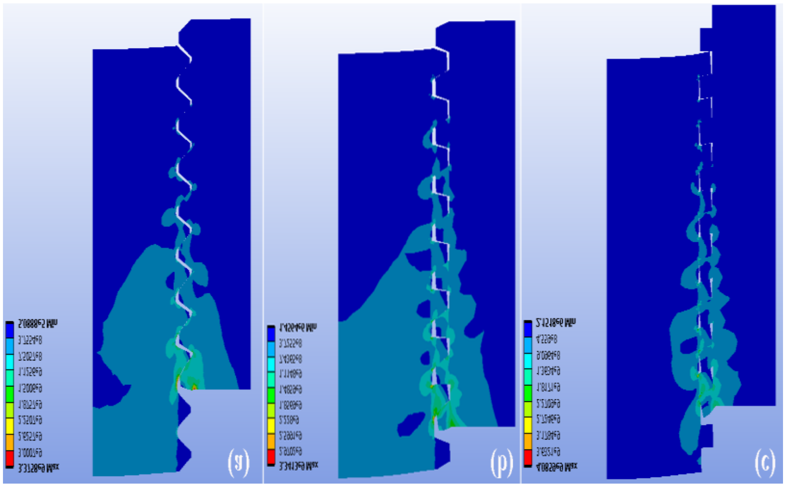


Fig. 4. 2D simulation of von Mises stress distribution on threads with (a) triangular, (b) trapezoidal (ACME), and (c) square profiles.

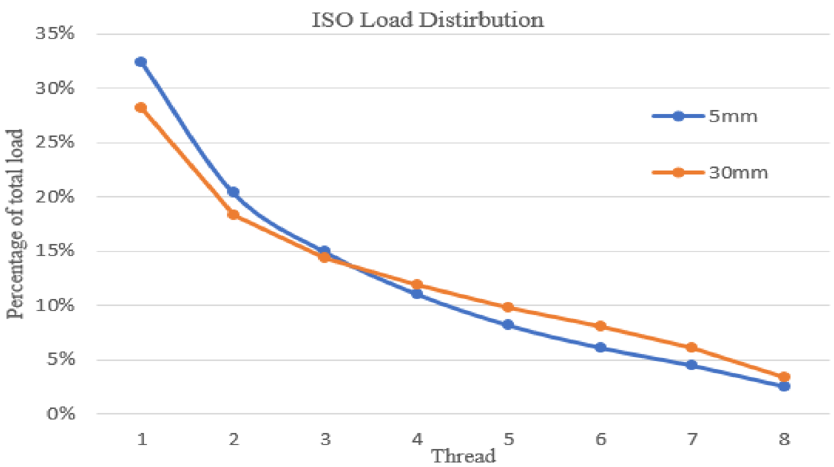


Fig. 5. Von Mises stress distribution on bolts with triangular (Metric) threads.

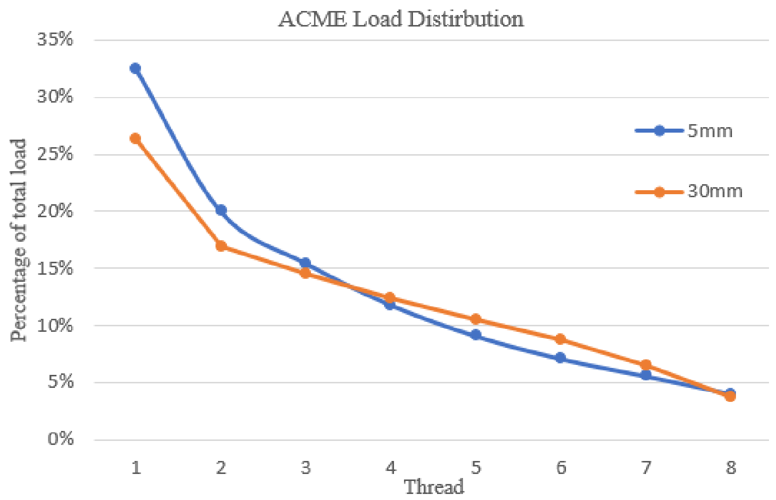


Fig. 6. Von Mises stress distribution on bolts with trapezoidal (ACME) threads.

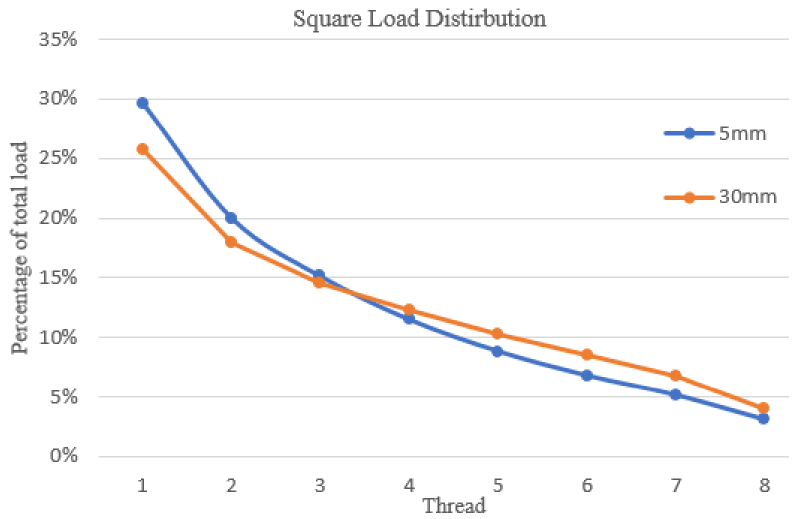


Fig. 7. Von Mises stress distribution on bolts with square threads.

As the bolt diameter increases, the continuity of stress distribution along the threads becomes more uniform. *Figs. 8–10* illustrate that square threads exhibit the highest continuity, followed by trapezoidal (ACME) threads, and then triangular (Metric) threads:

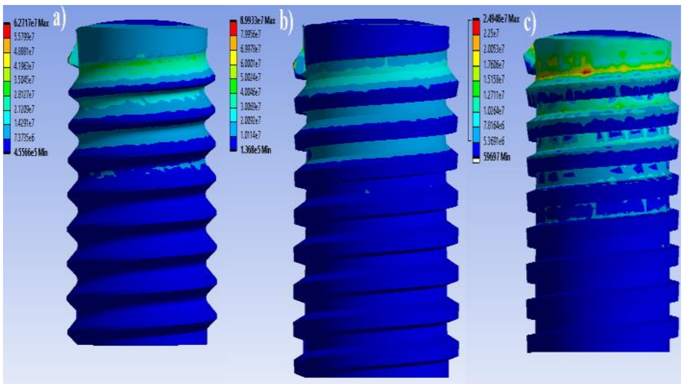


Fig. 8. 3D stress distribution of bolts with trapezoidal (ACME), triangular (Metric), and square threads at diameters of 5 mm and 30 mm.

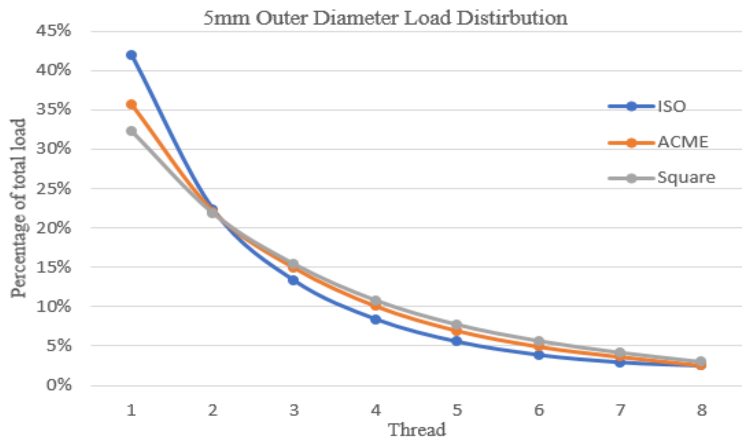


Fig. 9. Von Mises stress distribution for 5 mm diameter bolts: (a) triangular (Metric) thread, (b) square thread, and (c) trapezoidal (ACME) thread.

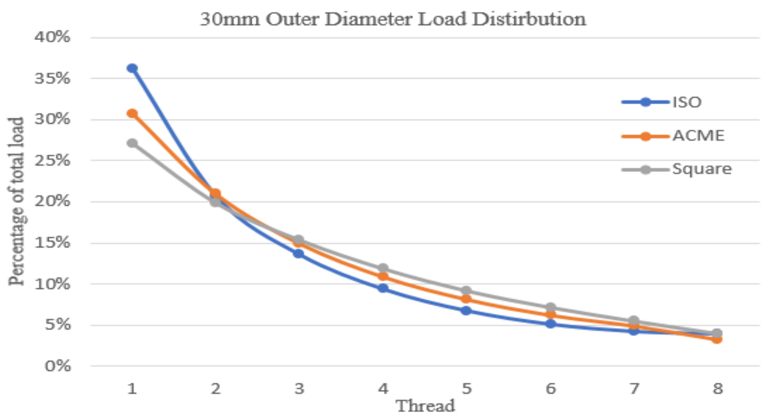


Fig. 10. Von Mises stress distribution for 30 mm diameter bolts: (a) triangular (Metric) thread, (b) square thread, and (c) trapezoidal (ACME) thread.

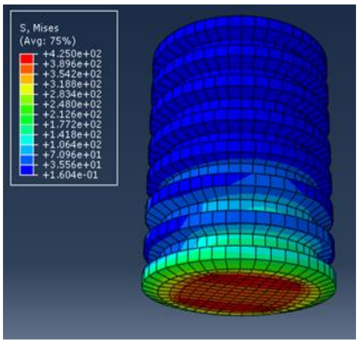
5 | Investigation of von Mises Stress and Pressure Distribution under Forces and Near-Fault Seismic Pulses for ACME, Square, and Metric Bolts with 5 mm Diameter

5.1 | Von Mises Stress Distribution in 5 mm Bolts

The von Mises stress distribution results (*Fig. 11*) indicate that stress concentration is more pronounced in ACME bolts compared to Square and Metric bolts. This suggests that ACME bolts are more sensitive to localized stress peaks, potentially increasing the likelihood of local damage in high-stress regions. Conversely, Metric bolts exhibit a more uniform and continuous stress distribution, reflecting a resilient mechanical response and a lower risk of localized failure under dynamic loading.

Figs. 12–14 illustrate the temporal variation of stress during the loading cycle. It is observed that Square bolts experience higher amplitude vibrations during the initial seismic pulses compared to ACME and Metric bolts. This behavior is attributed to the concentration of vibrational energy at specific contact points and the geometric characteristics of the threads. In contrast, Metric bolts demonstrate more uniform stress propagation during the initial pulses, indicating a better distribution of dynamic energy and reduced susceptibility to localized impact effects.

Overall, these findings highlight that bolt type and thread geometry critically influence both stress distribution and dynamic response of connections. While ACME bolts may be vulnerable under concentrated, short-duration loads, Metric bolts, with their more uniform stress distribution, provide enhanced resistance and stability under near-fault seismic conditions.



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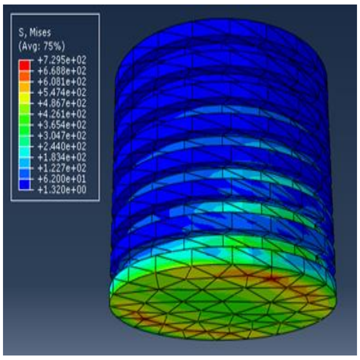

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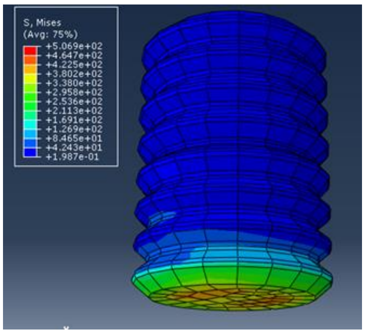


c.

Fig. 11. Stress distribution on 5 mm diameter bolts: triangular (Metric), square, and trapezoidal (ACME) threads; a. Trapezoidal (ACME) thread, b. Square thread, and c. Triangular (Metric) thread.

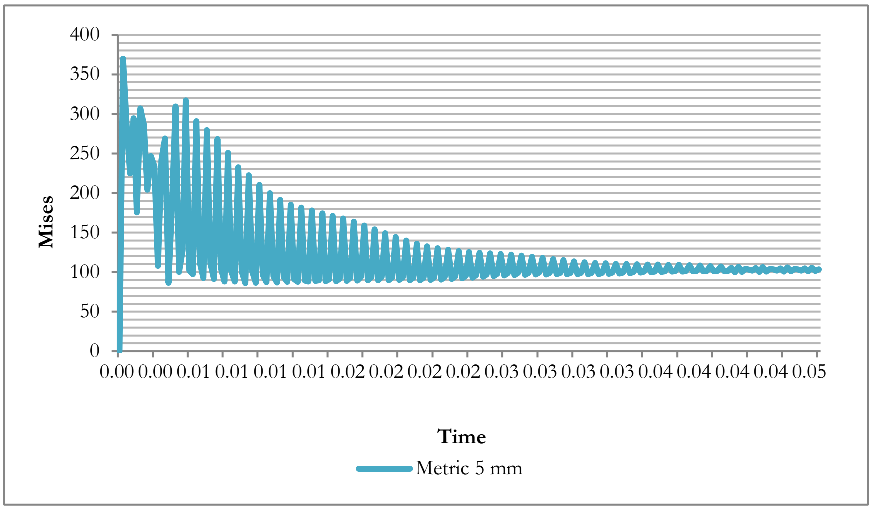


Fig. 12. Von Mises stress distribution under applied forces and near-fault seismic pulses on 5 mm diameter triangular (Metric) threads.

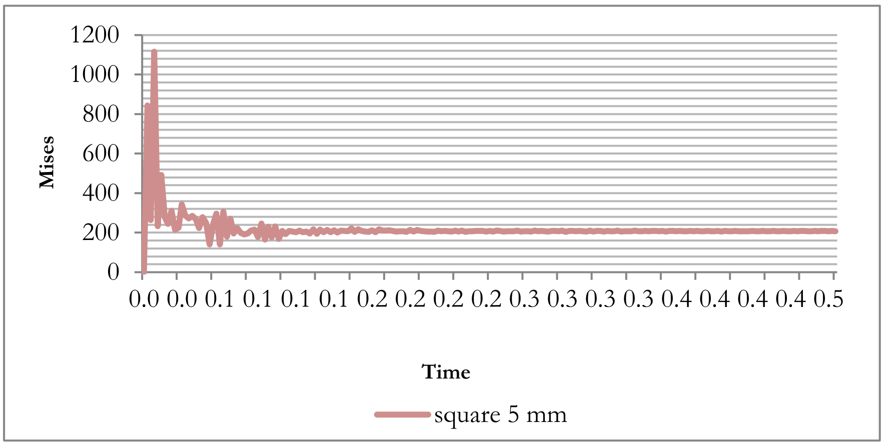


Fig. 13. Von Mises stress distribution under applied forces and near-fault seismic pulses on 5 mm diameter square threads.

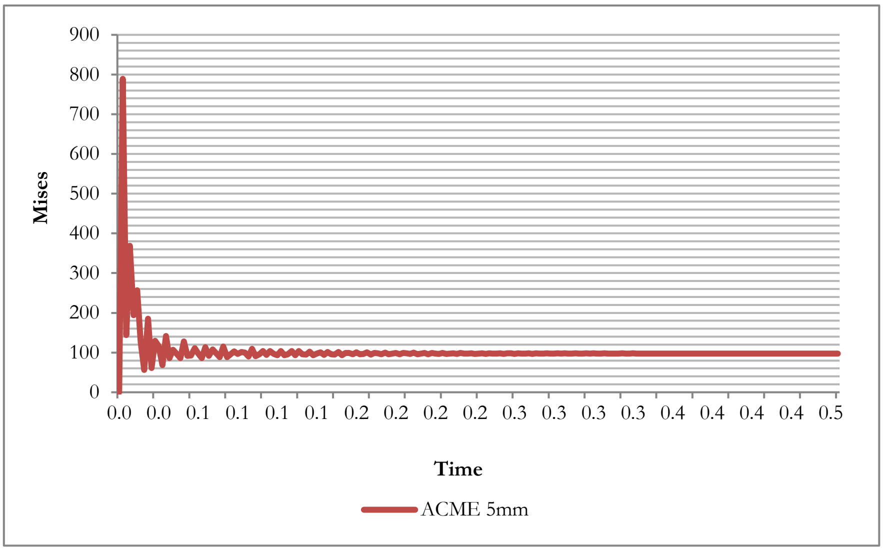


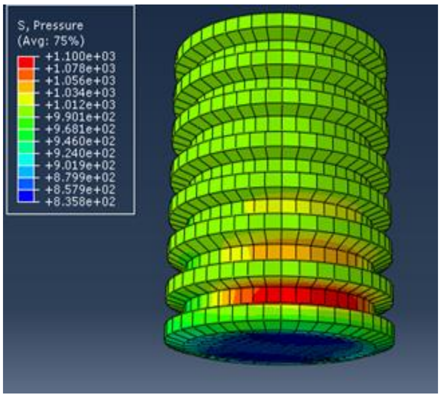
Fig. 14. Von Mises stress distribution under applied forces and near-fault seismic pulses on 5 mm diameter trapezoidal (ACME) threads.

5.2 | Pressure Distribution in 5 mm Bolts

The pressure distribution analysis (*Fig. 15*) reveals that Metric bolts exhibit higher pressure concentration compared to Square and ACME bolts. This localized pressure accumulation indicates potential vulnerable regions in Metric bolts under seismic excitation. In contrast, Square bolts demonstrate a more uniform pressure distribution along the bolt length, suggesting a more even force transfer and enhanced long-term performance under dynamic loads.

The temporal variation of pressure, as shown in *Figs. 16–18*, indicates that ACME and Metric bolts experience higher initial pressure fluctuations during the early seismic pulses compared to Square bolts. This behavior highlights the higher sensitivity of ACME and Metric threads to transient dynamic loads, whereas Square bolts maintain a more consistent pressure response, which supports better energy distribution and reduces the risk of localized failure.

Overall, the results emphasize that thread geometry plays a decisive role in the pressure response of bolts under near-fault seismic loading. Metric bolts, despite their higher stress concentration in certain regions, provide a stable dynamic response, while Square threads offer the most uniform pressure distribution, making them more suitable for applications where seismic resilience and load uniformity are critical.



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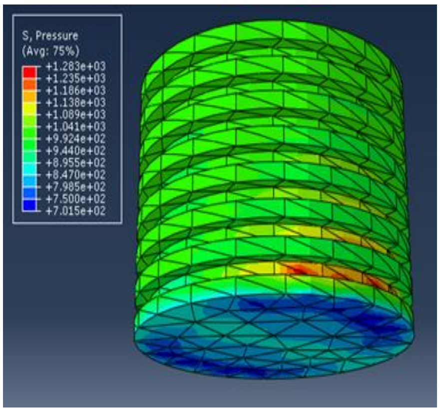

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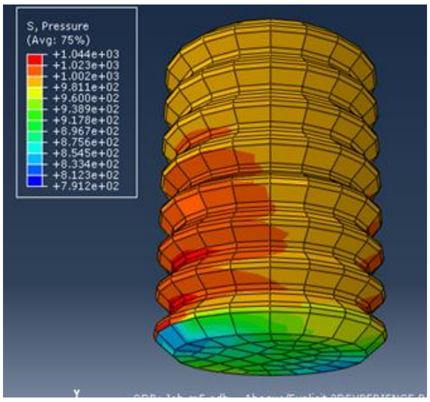


c.

Fig. 15. Pressure distribution on 5 mm diameter bolts: triangular (Metric), square, and trapezoidal (ACME) threads; a. Trapezoidal (ACME) thread, b. Square thread, and c. Triangular (Metric) thread.

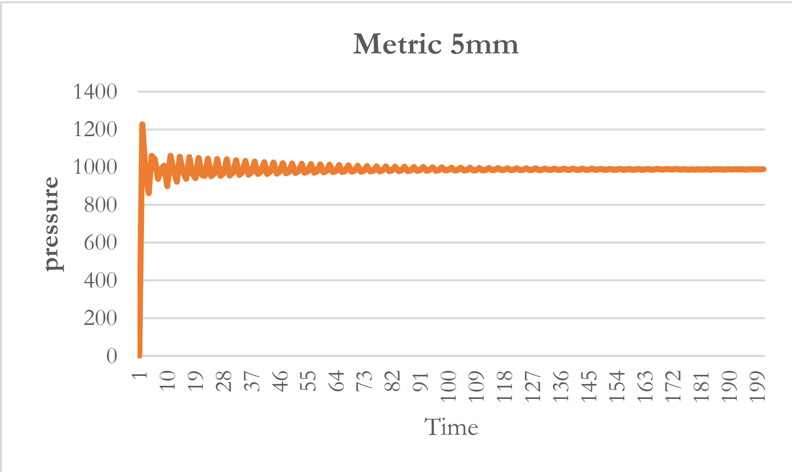


Fig. 16. Pressure distribution under applied forces and near-fault seismic pulses on 5 mm diameter triangular (Metric) threads.

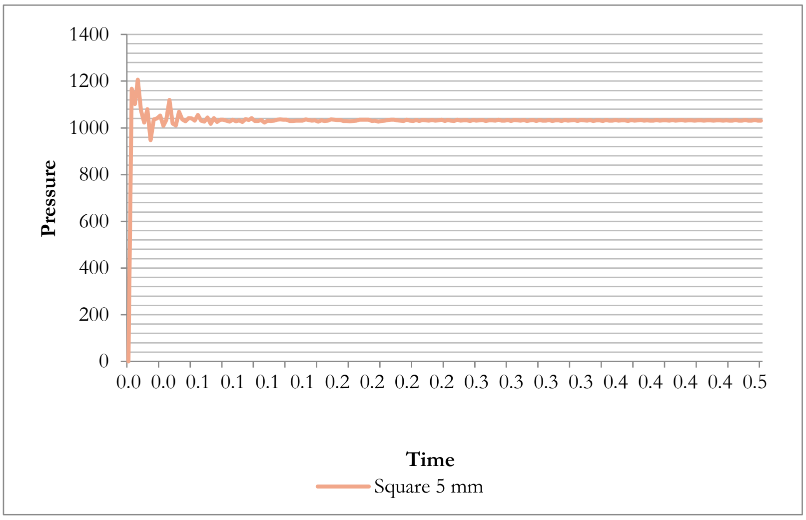


Fig. 17. Pressure distribution under applied forces and near-fault seismic pulses on 5 mm diameter square threads.

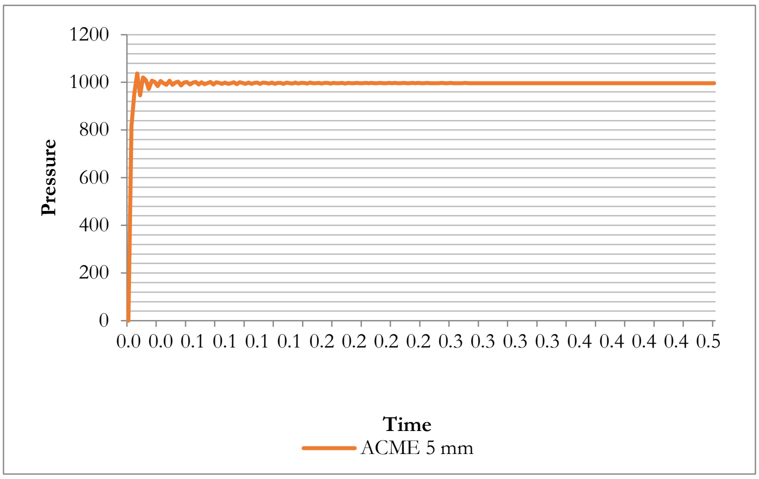


Fig. 18. Pressure distribution under applied forces and near-fault seismic pulses on 5 mm diameter trapezoidal (ACME) threads.

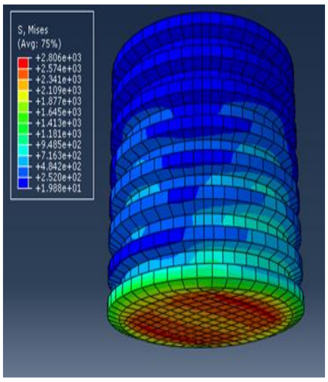
6 | Investigation of von Mises Stress and Pressure Distribution under Forces and Near-Fault Seismic Pulses for ACME, Square, and Metric Bolts with 30 mm Diameter

6.1 | Von Mises Stress Distribution in 30 mm Bolts

Based on *Fig. 19*, stress concentration is higher in Metric bolts compared to Square and ACME bolts. This indicates a higher likelihood of vulnerable points in Metric bolts. Additionally, the continuity of stress distribution is observed first in ACME bolts and then in Square bolts, reflecting differences in the bolts' response to static loading and initial stress distribution.

According to *Figs. 19* and *20*, which show stress variation over the loading cycle, the amplitude of seismic-induced vibrations in Metric bolts is higher during the initial pulses compared to ACME and Square bolts. This indicates that Metric bolts are more sensitive to initial dynamic loads. Conversely, Square bolts exhibit relatively uniform vibrations during the initial pulses, demonstrating a better distribution of vibrational energy and reduced impact effects.

Overall, this analysis highlights that the bolt type and thread geometry play a decisive role in stress distribution and the dynamic response of connections. Metric bolts, due to higher stress concentration, may require closer monitoring under severe dynamic loading, whereas Square bolts, with more uniform stress distribution, provide more stable performance under seismic excitations.



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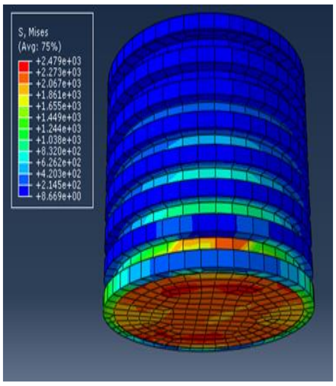

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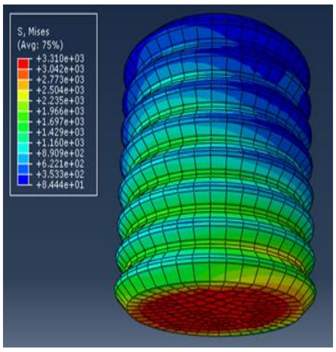

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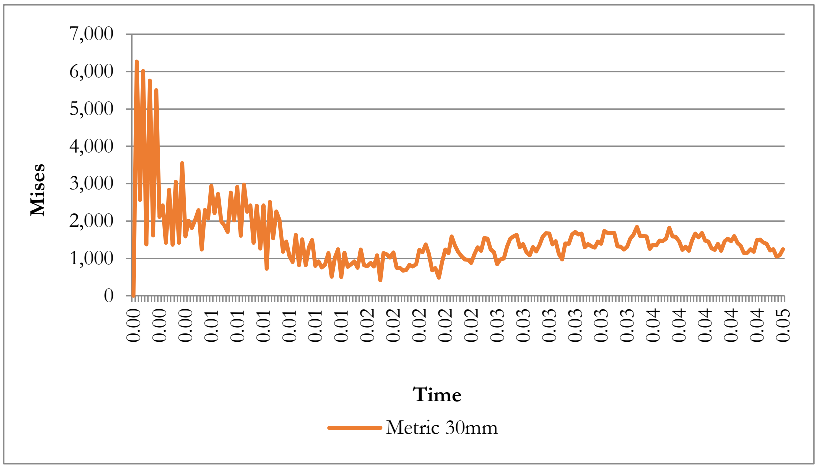
Fig. 19. Von Mises stress distribution for 30 mm diameter bolts: triangular (Metric), square, and trapezoidal (ACME) threads; a. Trapezoidal (ACME) thread, b. Square thread, and c. Triangular (Metric) thread.



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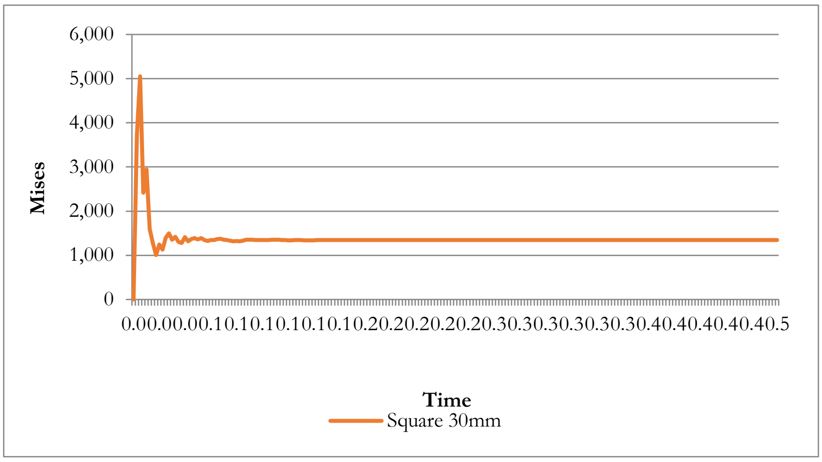

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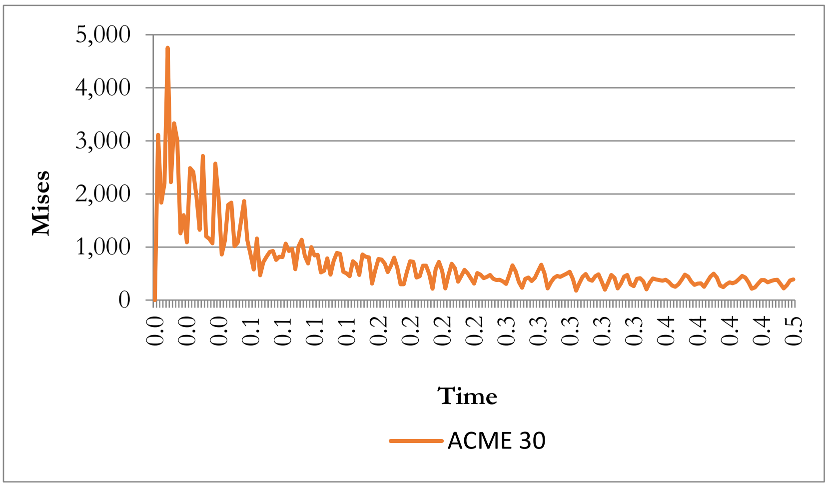


c.

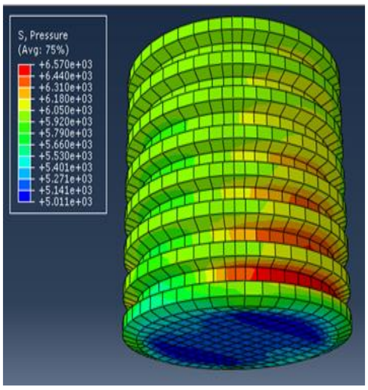
Fig. 20. Von Mises stress distribution for 30 mm diameter bolts: triangular (Metric), square, and trapezoidal (ACME) threads; a. Triangular (Metric) thread, b. Square thread, and c. Trapezoidal (ACME) thread.

6.2 | Pressure Distribution on 30 mm Diameter Bolts

Based on the pressure distribution results shown in *Fig. 21*, pressure accumulation in Metric and Square bolts is relatively uniform. Among these, Square bolts exhibit more continuous pressure distribution, indicating a better force distribution and reduced pressure concentration at specific contact points. This characteristic can lead to enhanced long-term strength and a lower likelihood of damage in these bolts.

Additionally, pressure variation over the loading cycle, presented in *Figs. 22–24*, indicates that the amplitude of seismic-induced vibrations in ACME bolts is higher during the initial pulses compared to Square and Metric bolts. This reflects the greater sensitivity of ACME bolts to initial impact loads. Conversely, vibrations are more uniform initially in Square bolts, followed by Metric bolts, compared to ACME bolts, indicating a better distribution of dynamic energy and reduced impact effects in these bolts.

Overall, this analysis demonstrates that bolt type and thread geometry play a key role in pressure distribution and the dynamic response of connections. Due to higher pressure concentration and vibration intensity during initial pulses, ACME bolts may require closer attention under dynamic loading, whereas Square bolts, with more uniform pressure and vibrations, provide more stable performance under seismic loads.



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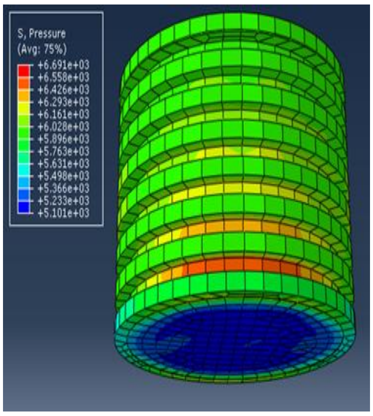

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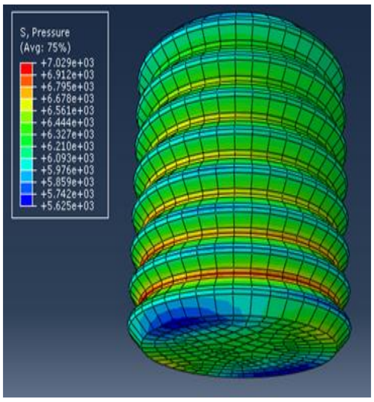


c.

Fig. 21. Pressure distribution on 30 mm diameter bolts: triangular (Metric), square, and trapezoidal (ACME) threads; a. Trapezoidal (ACME) thread, b. Square thread, and c. Triangular (Metric) thread.

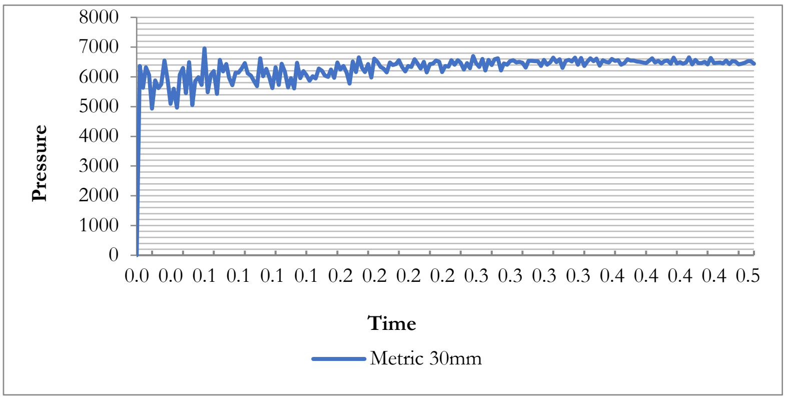


Fig. 22. Pressure distribution under applied forces and near-fault seismic pulses on 30 mm diameter triangular (Metric) threads.

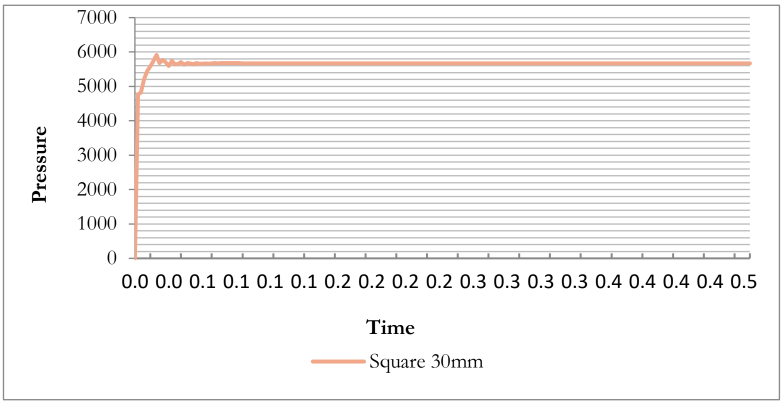


Fig. 23. Pressure distribution under applied forces and near-fault seismic pulses on 30 mm diameter square threads.

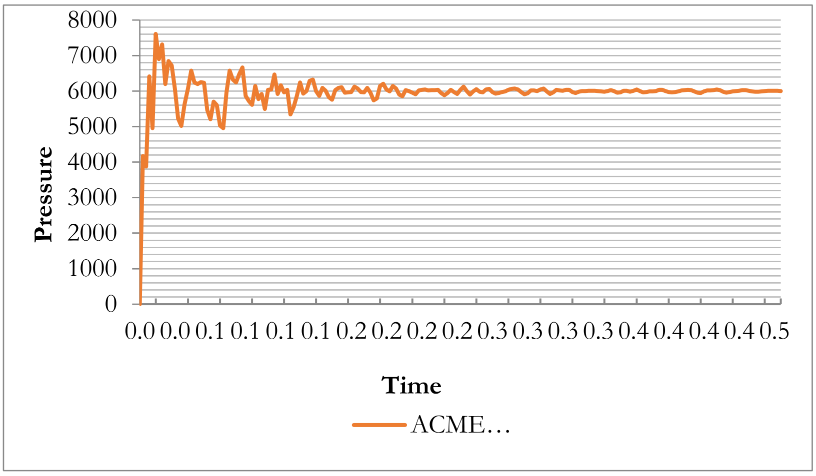


Fig. 24. Pressure distribution under applied forces and near-fault seismic pulses on 30 mm diameter trapezoidal (ACME) threads.

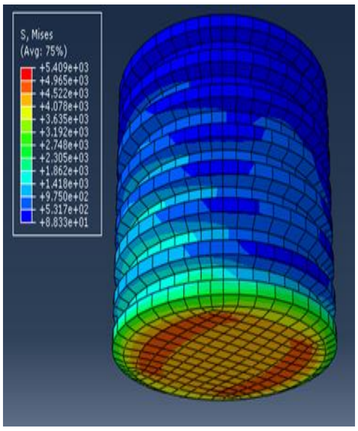
7 | Investigation of von Mises Stress and Pressure Distribution under Forces and Near-Fault Seismic Pulses for ACME, Square, and Metric Bolts with 56 mm Diameter

7.1 | Von Mises Stress Distribution in 56 mm Bolts

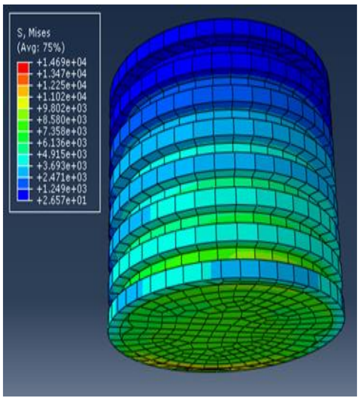
Based on the von Mises stress distribution results shown in *Fig. 25*, stress concentration is higher in Metric bolts compared to Square and ACME bolts. This concentration indicates a higher likelihood of vulnerable points in Metric bolts. Additionally, the continuity of stress distribution in ACME bolts is more pronounced than in the other types, reflecting a relatively more uniform stress distribution in these bolts.

According to the pressure distribution results presented in *Figs. 26–28*, which show stress variation over the loading cycle, the amplitude of seismic-induced vibrations is more significant in Square and Metric bolts compared to ACME bolts. In contrast, ACME bolts exhibit lower vibrations during the initial pulses, indicating less sensitivity to initial dynamic loads.

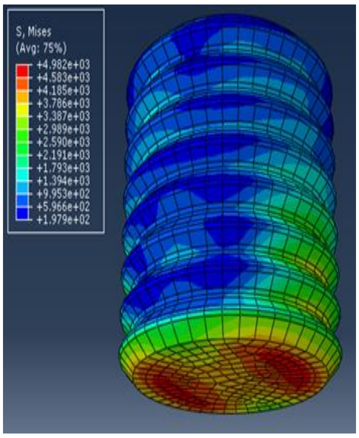
These results demonstrate that bolt type and thread geometry play a decisive role in stress distribution and the dynamic response of connections. Metric bolts, due to higher stress concentration, may require closer monitoring under severe loading conditions, whereas ACME bolts, with more continuous stress distribution, show relative resistance to initial dynamic changes and provide more stable performance during the early loading pulses.



a.

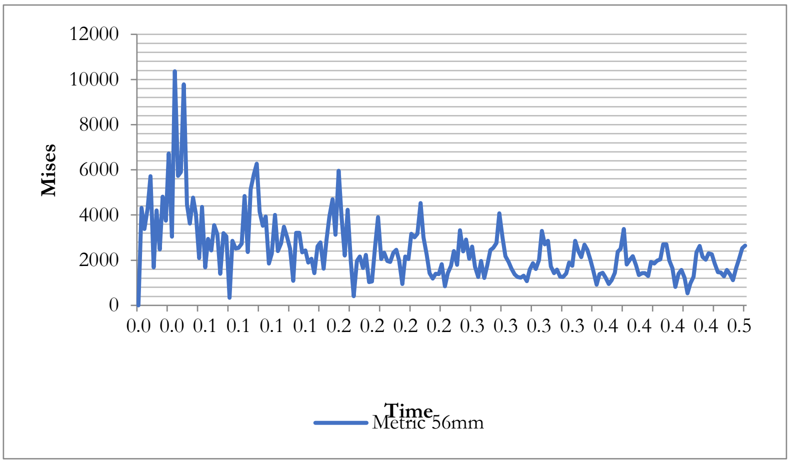


b.

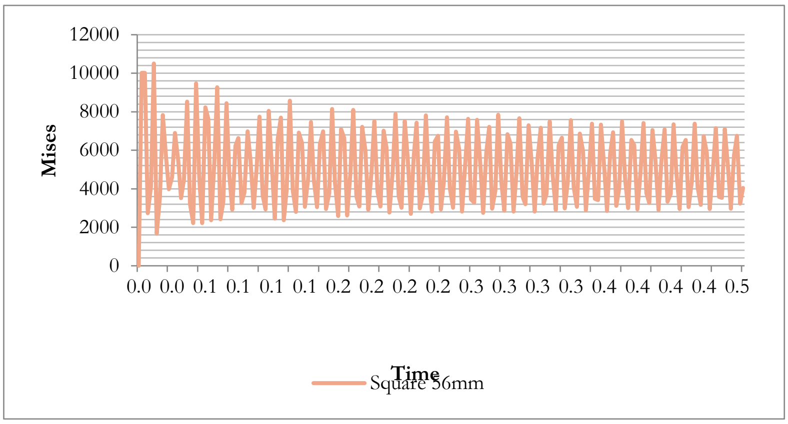


c.

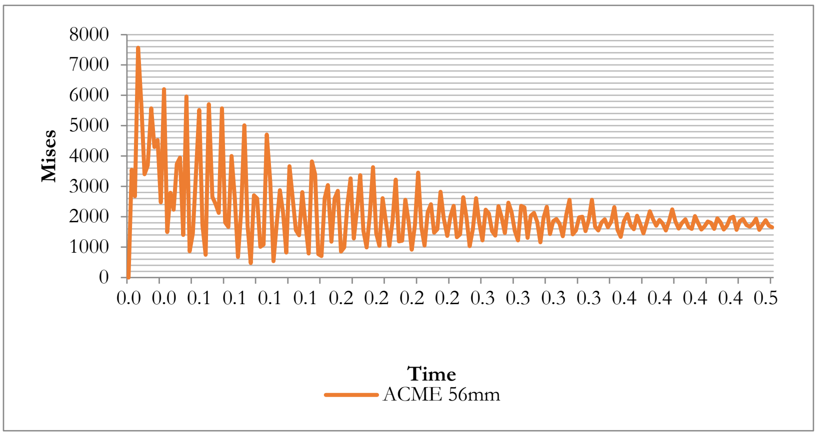
Fig. 25. Von Mises stress distribution for 56 mm diameter bolts: triangular (Metric), square, and trapezoidal (ACME) threads; a. Trapezoidal (ACME) thread, b. Square thread, and c. Triangular (Metric) thread.



a.



b.



c.

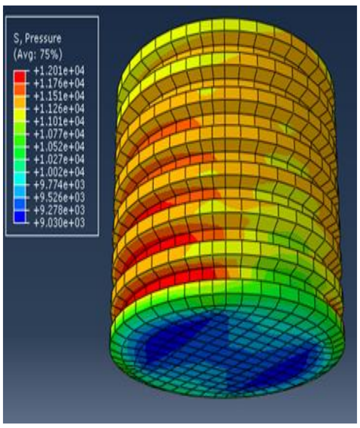
Fig. 26. Pressure distribution on 56 mm diameter bolts: triangular (Metric), square, and trapezoidal (ACME) threads; a. Triangular (Metric) thread, b. Square thread, and c. Trapezoidal (ACME) thread.

7.2 | Pressure Distribution in 56 mm Bolts

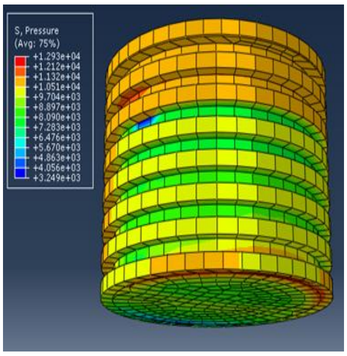
Based on *Fig. 27*, pressure accumulation is most pronounced in ACME bolts compared to Square and Metric bolts. This higher concentration suggests an increased likelihood of localized stress points in ACME bolts. In contrast, Square bolts exhibit more continuous and uniform pressure distribution, followed by Metric bolts, indicating superior force transfer and overall structural resilience.

Figs. 28–30 illustrate pressure variations over the loading cycle. Metric bolts show higher pressure absorption and greater amplitude of seismic-induced vibrations during the initial pulses compared to Square and ACME bolts. Conversely, the applied vibrations are more uniformly distributed first in Square bolts and subsequently in ACME bolts, relative to Metric bolts. This pattern demonstrates more efficient dynamic energy distribution and reduced impact effects in Square and ACME bolts.

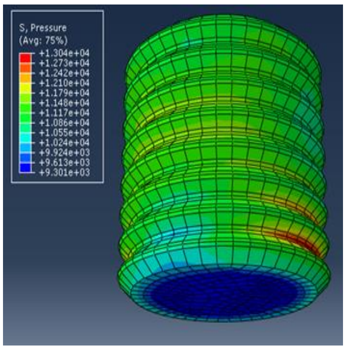
Overall, these findings emphasize that thread geometry and bolt type directly influence pressure distribution and the dynamic response of bolted connections. ACME bolts, with concentrated pressure, and Metric bolts, with higher initial pressure absorption, require careful monitoring under dynamic loading. In contrast, Square bolts, with more uniform pressure and vibration response, provide enhanced stability and performance under near-fault seismic excitations.



a.



b.



c.

Fig. 27. Pressure distribution on 56 mm diameter bolts: triangular (Metric), square, and trapezoidal (ACME) threads; a. Trapezoidal (ACME) thread, b. Square thread, and c. Triangular (Metric) thread.

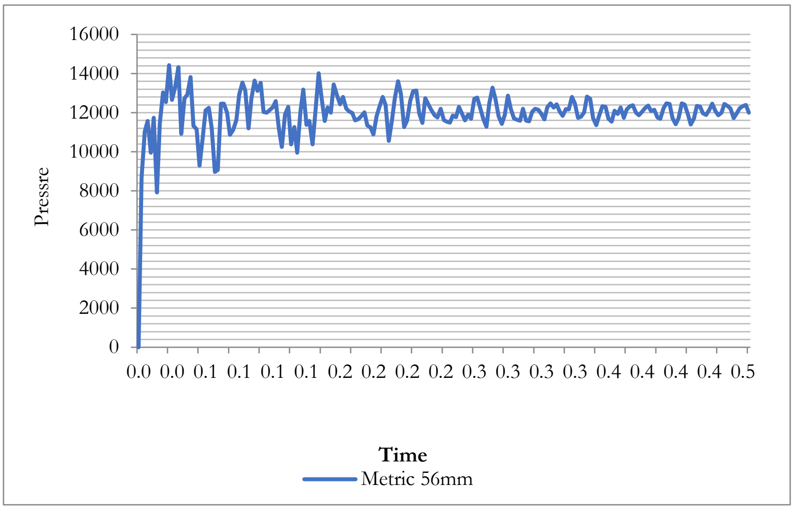


Fig. 28. Pressure distribution under applied forces and near-fault seismic pulses on a 56 mm triangular-thread (Metric) bolt.

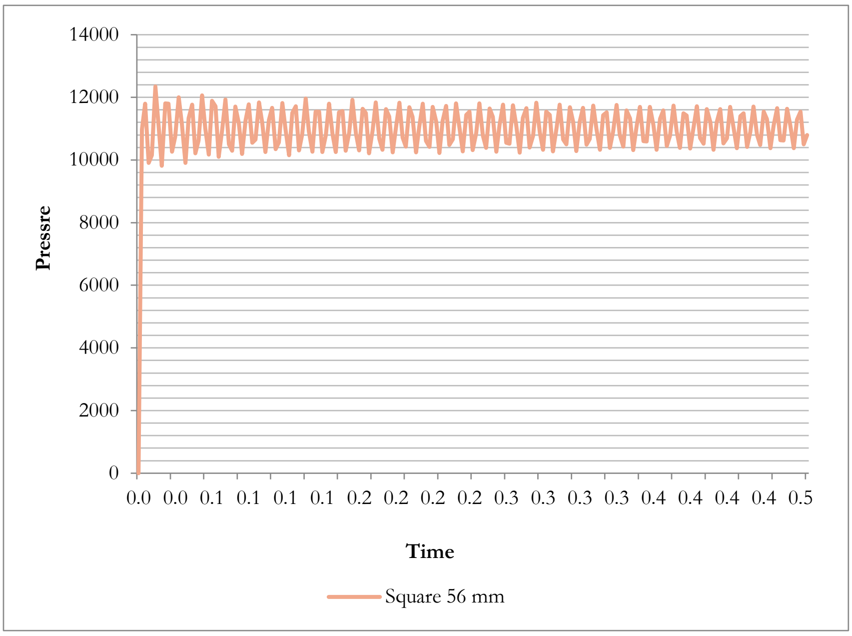


Fig. 29. Pressure distribution under applied forces and near-fault seismic pulses on a 56 mm square-thread (Square) bolt.

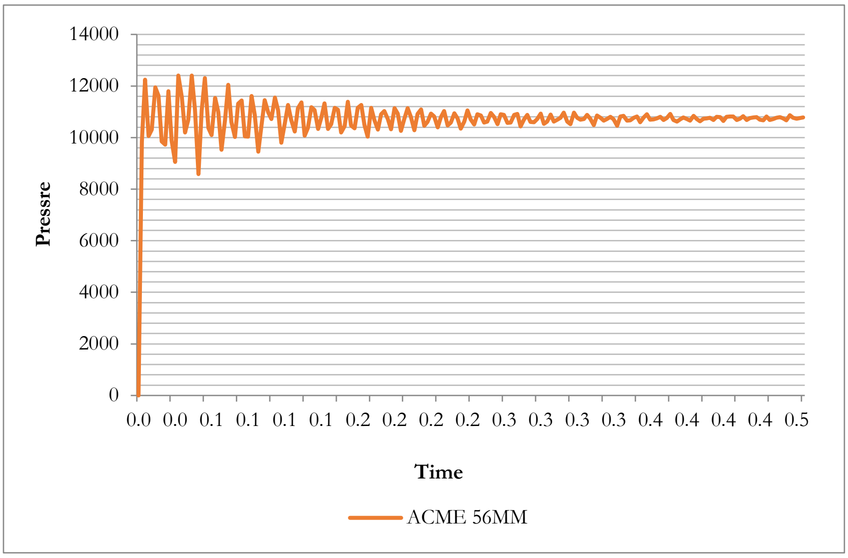


Fig. 30. Pressure distribution under applied forces and near-fault seismic pulses on a 56 mm trapezoidal-thread (ACME) bolt.

8 | Conclusion

Based on the analyses of von Mises stress and pressure distribution under applied forces and near-fault seismic pulses for triangular-thread (METRIC), square-thread (SQUARE), and trapezoidal-thread (ACME) bolts, the main findings can be summarized as follows:

5 mm diameter bolts:

I. METRIC bolts exhibit the most uniform von Mises stress distribution.

II. SQUARE bolts demonstrate superior pressure performance.

III. METRIC bolts maintain better stress continuity, whereas SQUARE bolts absorb higher pressure along their length, indicating a more uniform pressure distribution but slightly reduced performance under seismic-induced vibrations. ACME bolts show lower pressure absorption and a more consistent response to seismic vibrations, distinguishing their pressure behavior from the other types.

30 mm diameter bolts:

I. Stress continuity is highest in ACME bolts, followed by SQUARE bolts.

II. SQUARE bolts display enhanced performance under near-fault seismic excitations.

III. Pressure absorption is greatest in ACME bolts, followed by SQUARE and METRIC bolts. SQUARE bolts exhibit better pressure continuity and smoother vibration response along the bolt length.

56 mm diameter bolts:

I. Von Mises stress continuity is highest in ACME bolts, reflecting superior performance under seismic loads.

II. Pressure distribution is most uniform in SQUARE bolts, followed by METRIC bolts. SQUARE and ACME bolts demonstrate consistent pressure continuity and stable responses to seismic-induced vibrations.

Overall recommendations:

I. 5 mm bolts: Prefer METRIC bolts for stress performance and SQUARE bolts for pressure response.

II. 30 mm bolts: SQUARE bolts are generally suitable for typical construction connections.

III. 56 mm bolts: ACME bolts are recommended for industrial building connections due to improved stress continuity and dynamic performance.

8.1 | Future Research Directions and Industrial Implications

The present study provides several promising directions for future research. These include:

I. Developing high-fidelity three-dimensional finite element models of bolted connections.

II. Integrating AI and ML techniques to predict dynamic responses under near-fault seismic excitations.

III. Evaluating advanced materials and surface coatings with enhanced resistance to wear and fatigue.

IV. Coupling numerical simulations with experimental studies and real near-fault earthquake records to improve model robustness and predictive accuracy.

From an industrial perspective, the findings offer valuable insights for the seismic design of bolted connections in critical civil and industrial structures. Optimizing thread geometry can mitigate stress concentrations, enhance load transfer efficiency, and improve overall seismic performance. This study establishes a rigorous numerical framework that supports further research in smart structures and earthquake-resistant connection systems, enabling the development of more reliable, application-oriented design methodologies.

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