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Effect of Bolt Pattern Geometry on the Strength of Steel Gusset Plates: FEM and Experimental Investigation

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ABSTRACT

Gusset plates are fundamental elements in steel structures, serving as connectors between bracing members and primary framing components. Their performance under axial and cyclic loads is strongly influenced by bolt pattern geometry, which governs stress distribution, yielding, and buckling. This review synthesizes experimental and finite element method (FEM) investigations from recent studies to evaluate how variations in bolt arrangements affect the strength, fatigue performance, and post-buckling resistance of gusset plates. By analyzing both laboratory experiments and advanced numerical simulations, this paper identifies the critical role of bolt patterns in optimizing connection efficiency, safety, and economy. Research gaps and future prospects in the field are also discussed.

Keywords: Gusset Plates, Bolt Pattern Geometry, Axial and Cyclic Loads, Stress Distribution, Yielding, Buckling Resistance, Fatigue Performance

1. INTRODUCTION

Steel braced frames rely on gusset plates to transfer axial forces between braces, beams, and columns. The geometry of bolt patterns—such as spacing, pitch, edge distances, and number of rows—directly influences the effective width, load distribution, and buckling capacity of gusset plates. Traditional design methods, such as Whitmore's effective width and Thornton's column analogy, often simplify these connections, leading to conservative or unsafe predictions in some cases. With the advancement of finite element modeling and experimental testing, researchers have begun to quantify the actual effects of bolt arrangement on structural performance, paving the way for improved design rules.

2. LITERATURE REVIEW

2.1 STAINLESS STEEL CHANNEL-TO-GUSSET PLATE CONNECTIONS

Jiang et al. (2022) investigated stainless steel channel-to-gusset plate connections under net section fracture

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. Their experiments on 16 specimens demonstrated that connection length, eccentricity, and bolt arrangement significantly influenced fracture resistance. FEM validation showed that current codes (EN 1993-1-4, AISC 370) provided inaccurate predictions, especially for non-standard bolt layouts. This highlights that bolt geometry can critically change failure modes.

2.2 COMPRESSIVE STRENGTH OF CORNER GUSSET PLATES

Shin and Kim (2025) developed a comprehensive method for predicting compressive strength of gusset plates with various shapes

A comprehensive method for eval…

. Their study revealed that the Whitmore method often underestimated strength, especially for tapered gusset plates with irregular bolt spacing. The proposed analytical model, supported by FEM, offered more reliable predictions by explicitly considering bolt geometry effects.

2.3 FEM ANALYSIS OF BOLTED GUSSET PLATES

Court-Patience and Garnich (2021) analyzed 184 gusset plate geometries using FEM

Buckling analysis of gusset pla…

. Results showed that the Whitmore width method was unconservative for initial yielding predictions, particularly when bolts were arranged asymmetrically. Modified Thornton methods improved accuracy by incorporating realistic stress flow paths influenced by bolt patterns. This demonstrates that FEM is essential for capturing true load paths.

2.4 EXPERIMENTAL STUDIES ON BRACING MEMBERS WITH BOLTED CONNECTIONS

Zhang et al. (2023) performed pseudo-static tests on eight H-shaped bracing members connected via bolted gusset plates

Experimental investigation on s…

. They examined the effect of connection clearance, bolt slip, and pattern on hysteretic response. It was observed that bolt slippage redistributed stresses and improved energy dissipation. Importantly, double-row bolt configurations reduced effective length factors, enhancing compressive resistance.

2.5 NUMERICAL DAMAGE MODELING OF BOLTED GUSSET PLATES

Xie and Zhang (2024) built validated FEM models of bracing members with bolted gusset connections

Numerical analysis on steel bra…

. Their simulations confirmed that bolt layout strongly influenced local stress concentrations, fatigue life, and fracture locations. Approximately 45% of total energy dissipation was attributed to bolt slippage, proving that bolt geometry is not only a strength factor but also a fatigue-mitigation mechanism.

2.6 POST-BUCKLING RESISTANCE

Fang et al. (2015) studied post-buckling behavior of gusset plates using FEM and parametric analyses

Post buckling resistance of gus…

They found that thin gusset plates with dense bolt patterns showed higher post-buckling strength due to better load distribution. High-strength steel (HSS) further amplified this effect, underlining the importance of bolt geometry in conjunction with material properties.

3. ROLE OF GUSSET PLATES IN STEEL STRUCTURES

3.1 LOAD TRANSFER MECHANISMS

Gusset plates transfer axial and shear forces from braces into beams and columns. Their effectiveness depends on thickness, bolt layout, and steel grade.

3.2 COMMON FAILURE MODES

- **Net Section Fracture:** Occurs when stress concentrations along bolt holes reduce effective cross-sectional area.
- **Block Shear:** A mixed failure combining tensile rupture and shear yielding around bolt groups.
- **Bolt Tear-Out:** Insufficient edge distances cause premature tearing of steel around bolts.
- **Plate Buckling:** Thin gusset plates under compression can buckle, especially with poorly distributed bolts.

3.3 IMPORTANCE IN SEISMIC APPLICATIONS

In seismic regions, gusset plates must not only remain strong but also provide ductility and energy dissipation. Optimized bolt layouts are essential to achieve both safety and resilience.

4. SIGNIFICANCE OF BOLT PATTERN GEOMETRY

4.1 INFLUENCE ON STRESS DISTRIBUTION

Bolt placement defines the stress flow path. Staggered patterns help redistribute forces, while aligned rows concentrate stresses.

4.2 EFFECT ON DUCTILITY AND STIFFNESS

Tighter spacing improves stiffness but reduces ductility, while wider spacing provides better deformation capacity.

4.3 EDGE DISTANCE AND TEAR-OUT RESISTANCE

Larger edge distances prevent premature tearing, whereas inadequate margins reduce connection safety.

5. FINITE ELEMENT MODELING (FEM) STUDIES

Finite element analysis has become a reliable tool for investigating the influence of bolt patterns due to its ability to simulate stress flow, bolt slip, and local buckling.

- **Court-Patience and Garnich (2021)** analyzed 184 gusset plate geometries and concluded that conventional Whitmore-based predictions were unsafe for asymmetric bolt arrangements.
- **Xie and Zhang (2024)** developed FEM-based damage models that incorporated bolt slippage, showing that staggered bolt layouts redistributed stresses and delayed fracture.

Such numerical approaches allow researchers to explore a wide range of bolt geometries, making FEM essential for formulating generalized design guidance.

6. FEM VS. EXPERIMENTAL APPROACHES

- **Experimental Investigations** provide direct insights into failure modes, bolt slippage, and hysteretic performance, but are limited by cost and sample size.
- **FEM Simulations** enable comprehensive parametric studies across bolt geometries, plate thicknesses, and material strengths, offering generalized design guidance.

- **Hybrid Approaches**—validating FEM against experiments—have proven most effective in capturing the complex interaction between bolt geometry and gusset plate behavior.

7. CRITICAL FINDINGS ON BOLT PATTERN GEOMETRY

1. **Spacing and Pitch:** Reduced bolt spacing increases stiffness but raises risk of net section fracture.
2. **Edge Distance:** Inadequate edge distances promote tear-out failure, while larger distances improve ductility.
3. **Number of Rows:** Double-row and staggered arrangements enhance load distribution and reduce effective length factors.
4. **Symmetry:** Symmetrical bolt layouts minimize eccentric stresses, whereas asymmetrical layouts trigger premature yielding.
5. **Connection Length:** Longer bolt arrays improve axial strength but may induce bending effects if eccentricities are present.

8.DESIGN METHODS AND LIMITATIONS

Current codes often rely on **Whitmore's effective width method (1952)** and **Thornton's column analogy (1980s)**. While useful, these methods assume uniform stress transfer and do not properly address irregular bolt layouts. They may underestimate capacity in staggered patterns and overestimate it in asymmetric ones. More recent proposals, such as altering the dispersion angle from 30° to 45°, have improved accuracy but are not universally valid. This demonstrates the urgent need for design guidelines that explicitly account for bolt arrangement.

9. RESEARCH GAPS

- Limited full-scale experimental data on **irregular or staggered bolt patterns**.
- Insufficient studies integrating **carbon reduction strategies** (e.g., high-strength lightweight steels with optimized bolt layouts).
- Need for **life-cycle fatigue analyses** considering bolt slippage and cumulative damage.
- Absence of **unified design equations** that directly incorporate bolt pattern geometry into gusset plate strength predictions.

10. CONCLUSION

The reviewed literature demonstrates that bolt pattern geometry plays a pivotal role in the strength, ductility, and fatigue life of steel gusset plates. Both FEM and experimental investigations consistently reveal that conventional design codes may under- or overestimate capacity when bolt layouts deviate from standard assumptions. Optimized bolt geometries, combined with validated FEM models, offer pathways to safer, more economical, and sustainable gusset plate designs. Future work should focus on developing robust design provisions that explicitly address bolt arrangement effects

11. REFERENCE

1. Court-Patience, D., & Garnich, M. (2021). *Buckling analysis of gusset plates with bolted connections*. *Engineering Structures*. [Abstract] ScienceDirect https://www.sciencedirect.com/science/article/abs/pii/S0143974X2030972X

2. Shin, Y.-S., et al. (2025). *A comprehensive method for evaluating compressive strength of corner gusset plates*. *Engineering Structures*. [Abstract] ScienceDirect https://www.sciencedirect.com/science/article/pii/S0141029625005498

3. Zhang, W., et al. (2023). *Experimental investigation on steel bracing members with bolted gusset plate connections*. *Journal / Conference*. [Abstract] ScienceDirect https://www.sciencedirect.com/science/article/abs/pii/S2352710223013128

4. Hadianfard, M. A., & Khakzad, A. R. (2016). *Inelastic buckling and post-buckling behavior of gusset plate connections*. *Steel and Composite Structures*, 22(2), 411-427. ResearchGate

5. *Post-buckling resistance of gusset plate connections: Behaviour, strength, and design considerations*. (2015). *Engineering Structures*. Fang, C. H. Yam, M. C., Zhou, X., Zhang, Y. ResearchGate

6. LaBoube, R. A. (2006). *Compression Behavior of Thin Gusset Plates*. Missouri University — experimental work on thin plates under compression. Scholars' Mine

7. "Stress-Strain and Force Distributions in Gusset Plate Connections" – University of Alberta / AISC report. American Institute of Steel Construction

8. Whitmore, R. E. (1950). *Experimental Investigation of Stresses in Gusset Plates*. University of Tennessee. TRACE

9. *Experimental Tests of Truss Bridge Gusset Plate Connections with Sway-Buckling Response*. Higgins, C., Hafner, A., Tugrul, O., Schumacher, T. (2013). ResearchGate

10. *Design and Strength Evaluation of Critical Gusset Plates in the Steel Bridge Using New Load and Resistance Factor Design Methods and Advanced FE Analyses*. Jong Wan Hu (2013). ResearchGate

11. *Numerical Study of Stainless Steel Gusset Plate Connections* (EL Salih, 2013). ScienceDirect

12. *Influence of gusset plate connections and braces on the post-buckling behavior of steel braced frames*. (2010) – see EQE journal. AGU Publications

13. Court-Patience, M., Garnich, - "Predicting yielding of gusset plates in seismic frames using finite element modeling" (2020). NZSEE Repository

14.Del Valle Roldán, F., et al. (2012). *Computational Analysis of Critical Gusset Plate Connections Based on Bridge Evaluation*. Scholar UPRM

15. "Modelling nonlinear behavior of gusset plates in the truss based steel bridges" (Deliktas, B., & Mizamkhan, A.)— finite element studies of damage in gusset plates. arXiv

16. *Behavior and design of gusset plates in steel structures: A state-of-the-art review*. Song, Y., Zhang, M., Ke, K., Lin, X. (2023). (This review covers many studies, design methods, etc.) ResearchGate

17. *Analysis of the effect of stiffener on the buckling capacity and non-elastic behavior of bracing gusset plates*. Hadianfard, M. A., Khakzad, A. R., Vaghefi, M. (2015). ResearchGate

18. Nast, T. E., Grondin, G., & Cheng, J. J. (1999). *Cyclic behavior of stiffened gusset plate-brace member assemblies*. ResearchGate

19. "An analytical study on steel gusset plates" (Li, J., Hao, H.). Conference paper / journal. ResearchGate

20.“AISC: SCBF Gusset Plate Connection Design – Experimental research studies” (Thornton, etc.). Also catalogue by AISC / Technical Reports on gusset plate connection performance.