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Behavior Of CHS K-Joints Strengthend By Through-Bolts

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Abstract: Hollow structural sections are widely favored for their high efficiency and modern aesthetic appearance in numerous iconic global structures. The strengthening of joints in hollow structural sections is a critical aspect of steel structure construction, as these joints often serve as weak points, limiting the efficiency of the structure. Existing research has established through-bolts as an effective technique to reinforce T-joints in hollow sections. However, there remains a dearth of investigations focusing on K-joints. This scientific paper addresses this gap by leveraging previous experimental findings and conducting a comprehensive numerical study using finite element analysis. To analyze the behavior of circular hollow section K-joints strengthened with through-bolts. A parametric study is performed to elucidate the relationship between various geometric parameters of the joint and the strengthening effects of through-bolts in different arrangements. The joints are subjected to axial loading to simulate real-world conditions. This study sheds light on their potential as a viable solution for enhancing the structural integrity of circular hollow section K-joints. And provides valuable insights for practitioners and designers involved in steel structure construction.

***Index Terms* - Hollow sections; K-joints; Strengthening; Through bolts; Finite element modeling.**

I. Introduction

Hollow structural sections (HSSs) have emerged as a compelling alternative to open structural sections, offering superior mechanical properties that can significantly enhance the efficiency and performance of structural systems. Their closed shape grants them higher radii of gyration, resulting in increased buckling resistance and torsional resistance. While the advantages of HSSs are undeniable, it is crucial to acknowledge that the joints of HSS members may exhibit various collapse mechanisms, which could potentially compromise the overall integrity of the structure.

The endeavor to strengthen HSS joints and uphold the superior efficiency of HSS systems remains a prevailing concern in the research community. In 1983, Baines et al [1] experimentally introduced using through-bolts as a strengthening technique for rectangular hollow sections (RHS) under flexural loading. Since then, several studies followed that confirmed the feasibility of such technique [2][3]. In 2012, Aguilera et al [4] studied axially loaded T-joints RHS strengthened by through-bolts and reported a strength gain up to 30%. In 2015, Mohamed et al [5] studied stiffening effects of through-bolts on axially loaded Circular hollow sections (CHS) T-joints and reported up to 250% stiffness gain. In 2017, Iskander et al [6] experimental study reported a strength gain up to 50 % for CHS T-joints under brace axial loading strengthened by through-bolts.

Despite the widespread applications of CHS K-joints, there is limited research on their behavior when reinforced with through-bolts. To address this gap, we build upon existing experimental data for un-strengthened CHS K-joints and CHS T-joints strengthened by through-bolts. By developing calibrated Finite Element Models (FEMs), we aim to accurately simulate the joints failure mechanisms and evaluate the influence of through-bolts. Subsequently, we employ these validated models to perform a thorough parametric study, exploring the impact of various geometric parameters and different through-bolt configurations on K-joint behavior.

II. Finite Element Modeling

2.1 Finite Element Model Setup

Utilizing ABAQUS CAE [7], a non-linear Finite Element (FE) analysis software, calibrated FEMs were generated. The adopted FE strategy closely emulates the approach proposed by Dexter et al. [8], to produce precise FEMs validated against Kurobane's experimental investigation on CHS K-joints [9]. Subsequently, this identical strategy was applied to simulate Iskander's enhanced T-Joints [6], to verify the model's capability in capturing the influence of through-bolts on K-joints behavior.

For K-joints, only one half of the joint is modeled with symmetry condition imposed in out-of-plane direction following the dimension and test setup used by Kurobane [9], as shown in Figure 1a. For T-Joints, only one quarter of the joint is modeled with symmetry conditions imposed in planes of symmetry. FEMs followed the dimensions and test setup used by Iskander et al. [6], as shown in Figure 1b. Detailed modeled specimens' dimensions are presented in Table 1.

a) Developed FEM for K-joint b) Developed FEM for T-joint

Figure 1 Developed finite element models

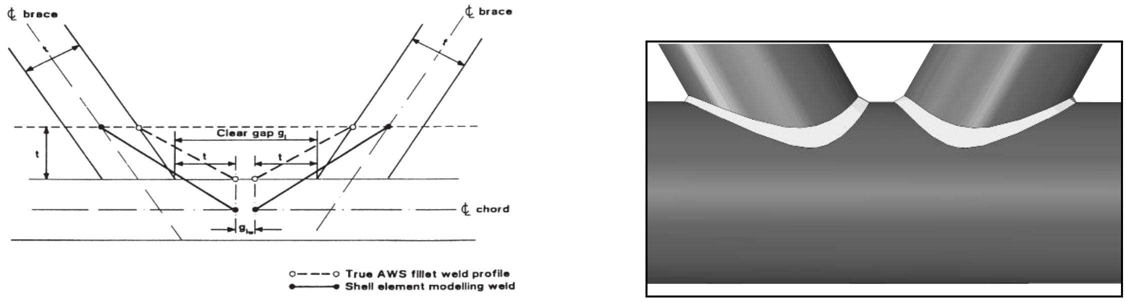
Table 1: Dimensions of tested specimens [6], [9]

	Specimen ID	Gap [mm]	d_o [mm]	t_o [mm]	d_1 [mm]	t_1 [mm]	No. of bolts	Spacing [mm]
Gapped K-Joint [9]	G2A	29.5	216	7.82	165	3.51	N/A	
	G2B					4.32		
	G2C					5.28		
Overlapped K-Joint [9]	I1A	-30	216	4.42	165	3.51	N/A	
	I3C			7.9		5.28		
	L1A	-90		4.42		3.51		
	L3C			7.9		5.28		
T-Joints [6]	C-0-000	N/A	168.3	3.3	141.3	5.12	N/A	
	S-1-000						1	N/A
	S-2-050						2	50
	S-2-100							100
	S-3-050						3	50
	S-3-100							100

d_o: Chord outer diameter d_1: Brace outer diameter t_o: Chord thickness t_1: Brace thickness

2.2Weld between Braces and Chord

Lee et al [10] investigated different modeling techniques for K-joints. They concluded that weld modeling as a ring of shell elements around each intersection produced accurate results. This approach is implemented in this study for both (K) and (T) joints to maintain consistent modeling technique for all the specimens, as shown in Figure 2.



a) Weld modeling by Lee [10] b) Weld modeling in the current study

Figure 2 Weld modeling

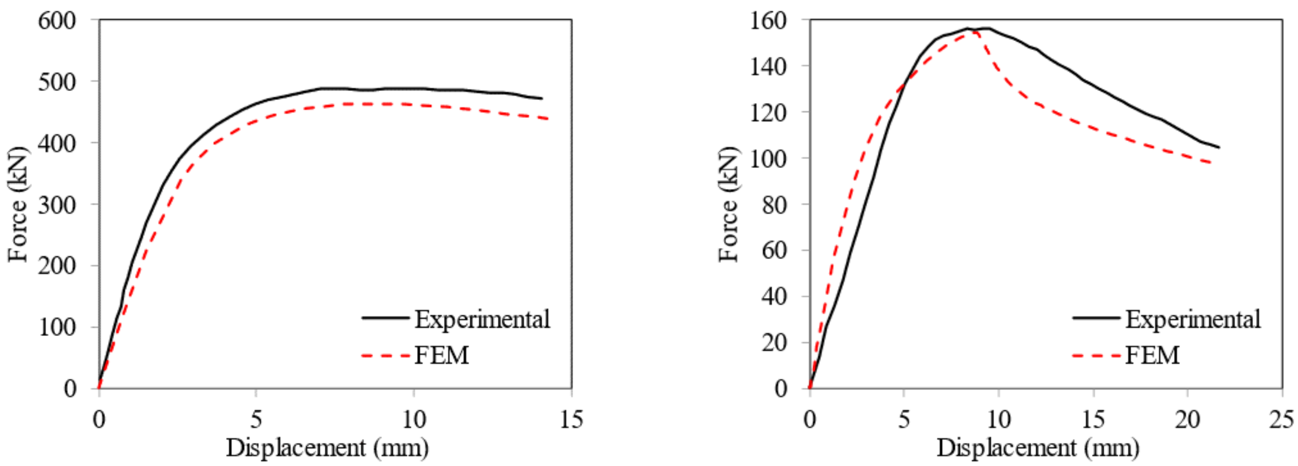
2.3 Through-Bolts Modeling

Bolts modeling is considered a crucial aspect in the strengthened FEM. Bolts need to be accurately modeled to capture the complex bolt-to-chord interaction behavior. S4R shell elements are used to model the washers and bolt heads. The bolt thread is modeled using C3D8R solid elements to provide lateral surface to the thread for contact interactions with the chord. To prevent the bolt from penetrating the chord, surface-to-surface interaction is defined between the washer inner surface and the chord outer surface. And to the thread contained in the bolt hole, node-to-surface interaction is defined between the surface of the thread and the nodes along the bolt-hole perimeter. For both contact interactions, hard contact algorithm is used, and friction coefficient of 0.3 is used for sliding along the contact surfaces.

2.4 Verification of FE Results

A comparative analysis, with two independent experimental results, was conducted for the FE modeling validation. For K-joints, the displacement was measured at a specific location on the compression brace, positioned 519 mm from the chord's centerline as reported in the experimental setup. Remarkably, the FEM proficiently replicated both the stiffness and the comprehensive load-displacement behavior of the actual joints, as shown in Figure 3a. In the case of T-joints, although a minor divergence in stiffness between the FEM and experimental data emerged, the outcomes exhibited notable alignment with the overall experimental behavior, as demonstrated in Figure 3b.

FEMs results were compared to the experimental results of all specimens mentioned in Table 1 from references [6] and [9] and the comparison between the experimental and FE failure loads, shows a good agreement with 99.8% average accuracy and 1.8% standard deviation.



a) K-joint specimen (I1A) b) Strengthened T-joint specimen (S-3-050)

Figure 3 Load-displacement results for FEMs

III. Parametric Study

A parametric study is then performed to investigate the effect of different bolt patterns on the strength of K-joints using the calibrated FEMs, a research matrix of (110) specimens was identified to investigate the relation between different bolt patterns utilizing different gaps.

3.1 Overlapped K-Joints

Figure 4 shows the load displacement curves for several overlapped K-joints. Annotations are added to show the strength of the control specimen with the corresponding displacement, the maximum and minimum strength gains each with corresponding strength and displacement values. A deformation limit of 3% of the chord diameter is shown as a vertical line in the graph.

In all the specimens using (4-100) bolt pattern (4 bolts, 100mm spacing) yielded the maximum strength gain regardless of the overlap size. It should be noted that all the overlapped specimens strengthened and un-strengthened exhibited ductile failure where the ultimate strength was determined due to deformation limit of 3% of chord diameter, as shown in Figure 4.

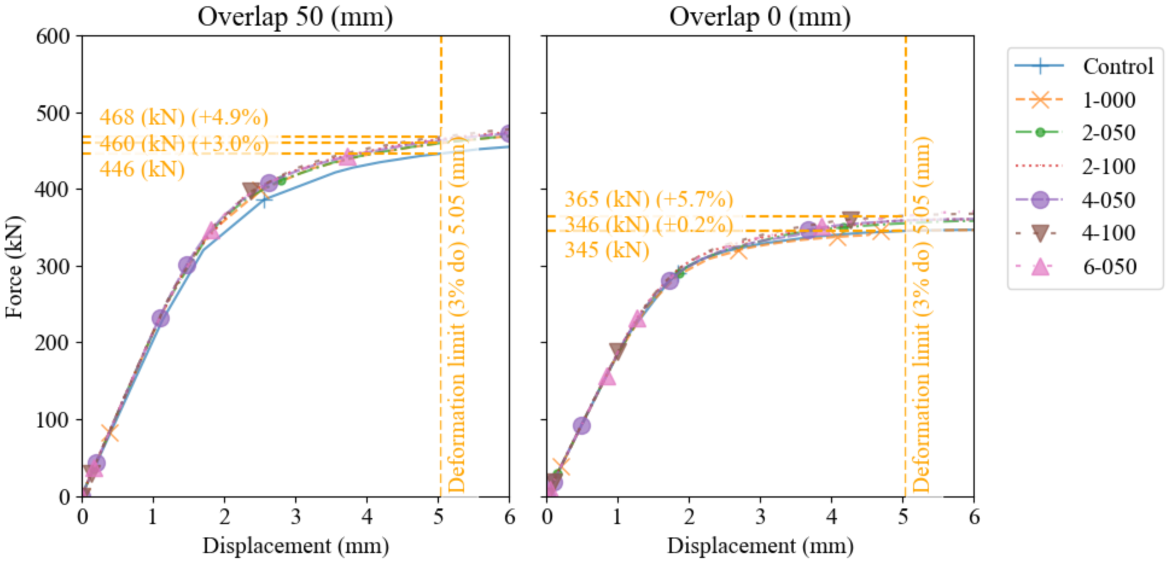


Figure 4 Load-displacement results for strengthened overlapped k-joints

From the investigated cases, the bolts pattern corresponding to the maximum strength gain is (4-100) pattern which covers the largest strengthened zone length of 300 mm. A directly proportional relationship is proposed between the maximum strength gain and the length of the strengthened zone, which can be observed in Figure 5.

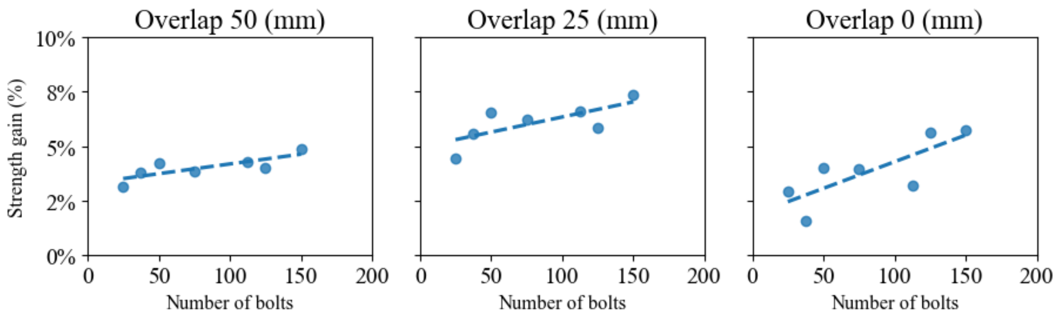


Figure 5 Strength gain vs length of strengthened zone for overlapped k-joints.

3.2 Gapped K-Joints

3.2.1 Bolts Positioned About Geometric Center

Figure 6 shows load-displacement curves for several strengthened gapped K-joints in comparison to their control specimens. Unlike the overlapped joints, the un-strengthened gapped joints did not fail due to reaching their deformation limits. However, with the use of through-bolts, these joints were able to reach their deformation limits. Consequently, most of the gapped joints exhibited a significant increase in strength when compared to the overlapped ones.

For joints strengthened by a single through-bolt at the geometric center, minimal strength gain was observed (0.3% for a 25 mm gap and -2% for a 75 mm gap). This indicates that bolts placed at the geometric center have a limited effect on the strength of the K-joint, as illustrated in Figure 6.

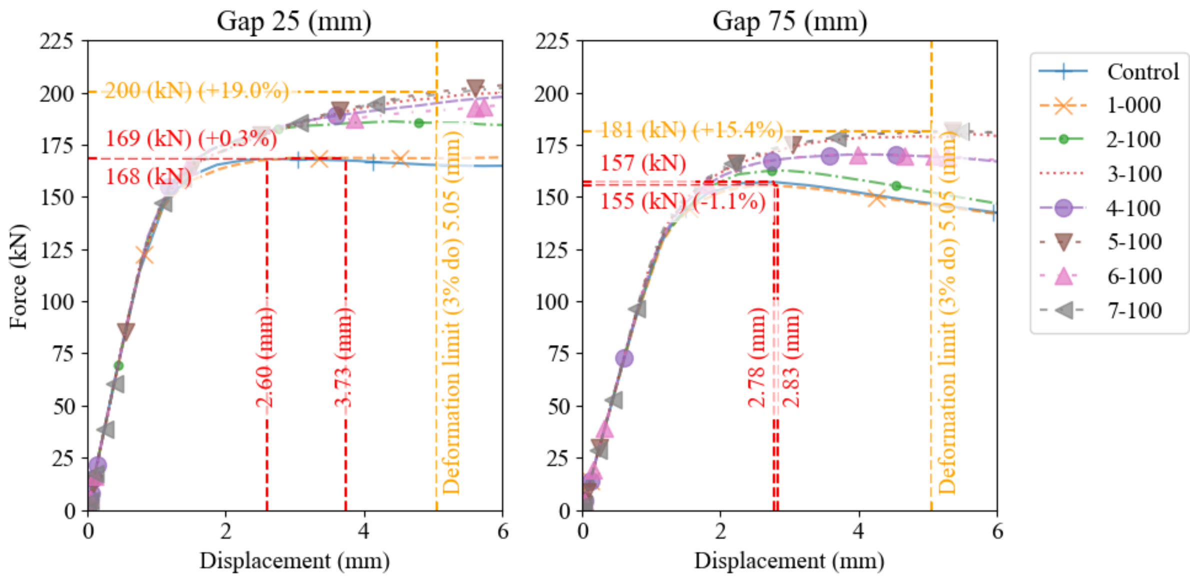


Figure 6 Load-displacement results for strengthened gapped k-joints

Figure 7 shows the percentage of strength gain for (G25-G75) specimens. These specimens demonstrate the complex behavior exhibited by the strengthened joints. Notably, there is no consistent relationship discernible between factors such as the number of bolts, bolt spacing, or the length of the strengthened zone, and the corresponding percentage of strength gain. However, certain overarching trends can be inferred if we neglected the discrepancies.

Firstly, the strength gain tends to increase with the length of the strengthened zone, up to a certain threshold beyond which increasing the zone yields diminishing returns. This implies that there exists an optimal range for the length of the strengthened zone to maximize the strengthening effect.

Secondly, bolt patterns with an odd number of bolts exhibit different behavior compared to patterns with an even number of bolts regardless of having the same strengthening zone length. This suggests to have specific positions of individual bolts within the pattern that affects the strengthening behavior of the joint.

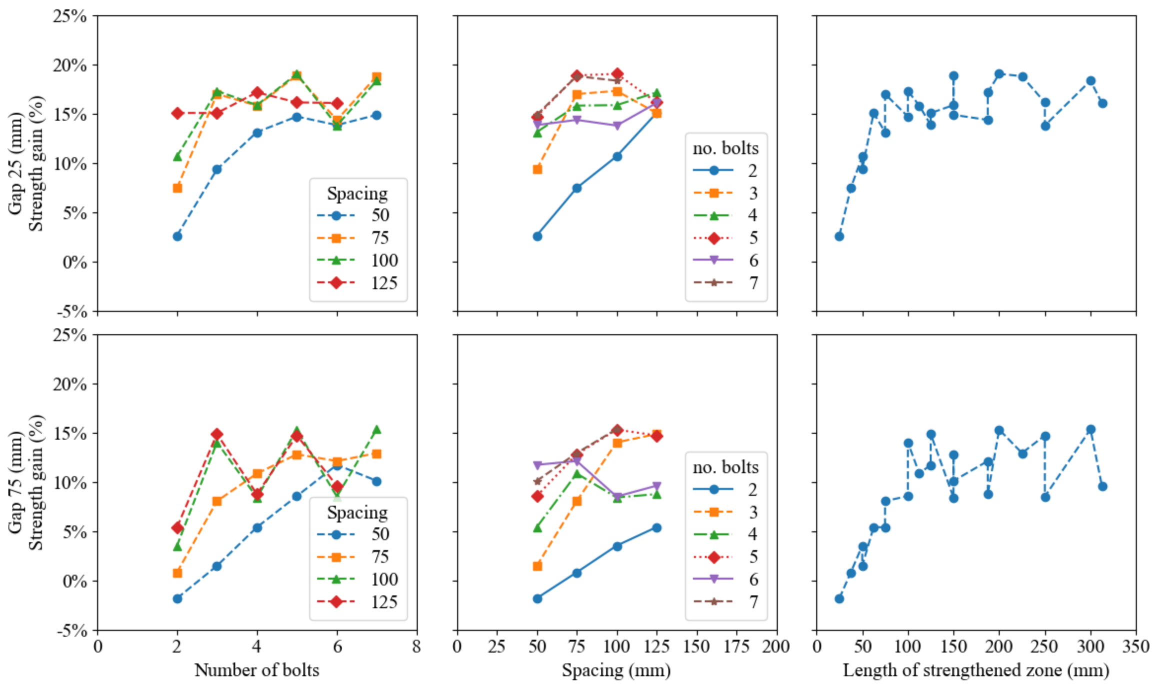


Figure 7 Strength gain vs number of bolts and spacing for (G25-G75) gapped k-joints

3.2.2 Bolts Positioned Compression Brace Center

Aiming to achieve a more uniform behavior, another attempt was made by placing the bolt patterns centered about the centerline of the compression brace as shown in Figure 8 rather than the geometric center of the joint.

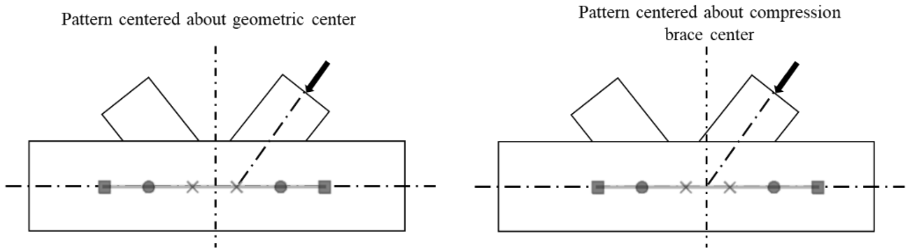


Figure 8 Different arrangements of bolt patterns

Figure 9 shows that when K-joints are strengthened using bolt patterns centered around the compression brace, the behavior of the joints exhibits greater consistency. This is reflected in the percentage of strength gain, which varies within a narrower range of 5%. This stands in contrast to the scenario where bolts are arranged around the geometric center, where there is a more significant difference of 15% between the highest and lowest strength gains. It is worth mentioning that this comparison excludes the single bolt case.

For the case of a single bolt, a low strength gain of approximately 7% was achieved by all the specimens utilizing different gaps. This is much more significant than strength gain by a single bolt placed at the geometric center.

Figure10 shows the relationship between strength gain and various bolt pattern parameters. It reaffirms the absence of any concrete relations. These findings align with the observations made when bolts were positioned around the geometric center.

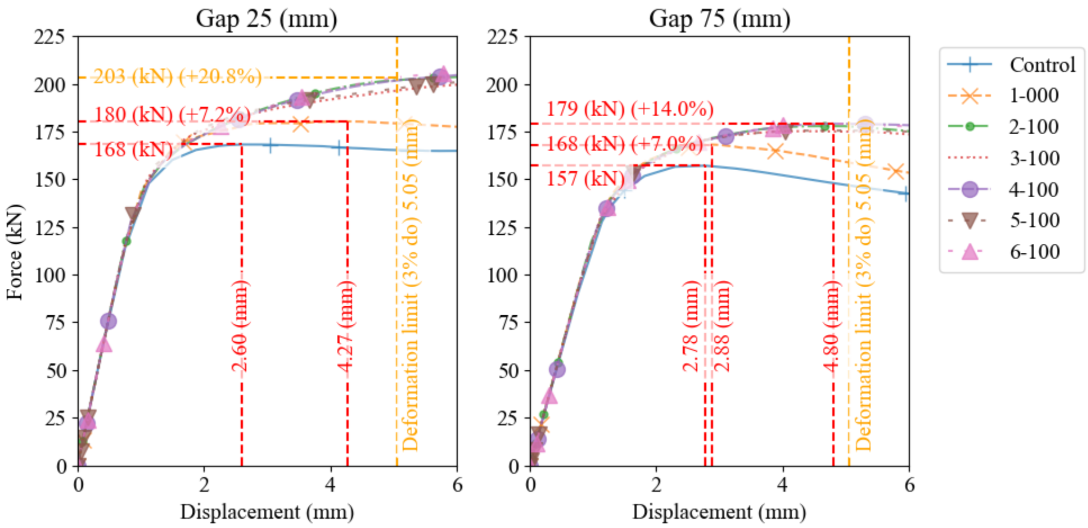


Figure 9 Load-displacement results for bolts positioned around the compression brace center

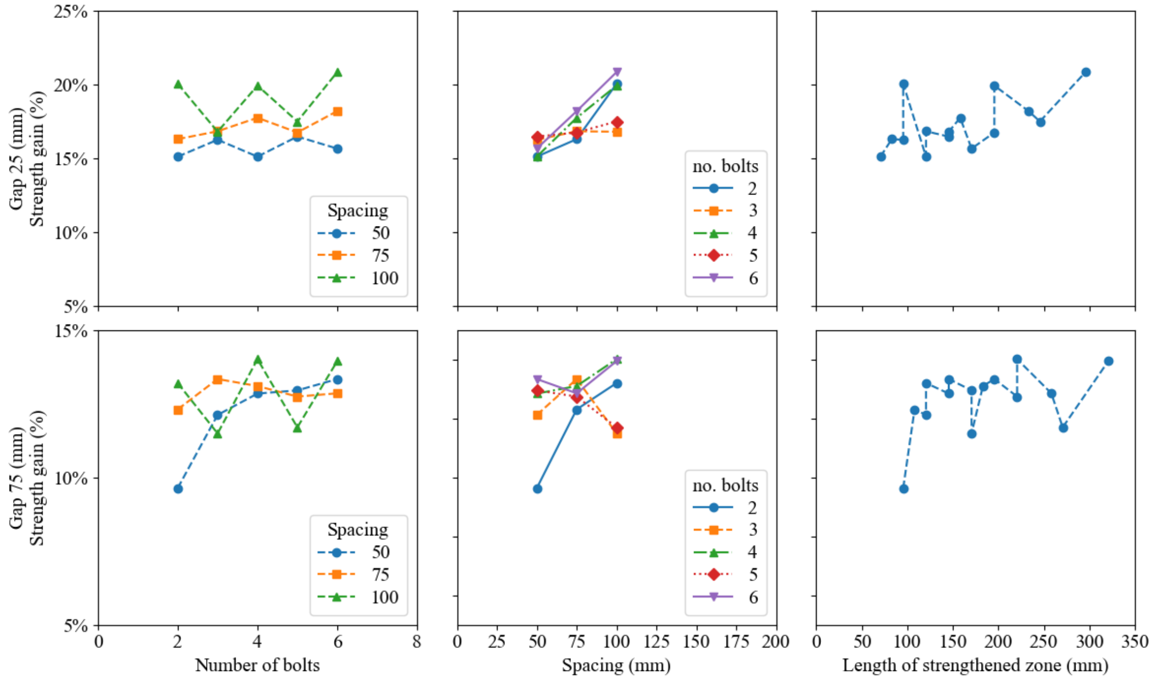


Figure 10 Strength gain vs number of bolts and spacing for bolts positioned around the compression brace center.

3.2.3Envelopes Study

Figure 11 shows the relationship between the strength gain and the strengthened zone length expressed as the distance between the geometric center and the last bolt placed in each pattern. This metric was illustrated above in Figure 7, but here a different approach is considered. An envelope is drawn that encapsulates the results of all the bolt patterns. Bolt patterns on the envelope curve are given a number to represent the number of bolts in the corresponding pattern.

On examining the envelope curve three main points can be observed. Firstly, the previously mentioned discrepancies in the relationship between the strengthened zone length and strength gain diminish. Upon considering the envelope curve, a consistent relationship emerges where the strength gain is directly proportional to the strengthened zone length up to a certain limit where it reaches saturation and adding extra bolts beyond this zone have a negligible effect.

Secondly, this saturation point is achieved by a single bolt on the compression side of the joint. For G25, saturation was achieved at (G25-3-075) which is an odd pattern having one bolt at the geometric center, one bolt on the tension side and a single bolt on the compression side of the joint. Another case is (G25-3-075), where it achieved strength gain of 17.5%, which is 92% of the maximum strength gain achieved by (G25-5-075). The same observation is maintained for G50 where saturation was achieved by (G50-3-100) achieving strength gain of 14.5% which is 95% of the maximum strength gain achieved by (G50-3-100).

Furthermore, as for the case of G25, the saturation was achieved by (G25-3-075), other bolts pattern has the same length of strengthening zone like (G25-4-50) still achieved lower strength gain. The only difference between the two bolt patterns is that the latter has an extra bolt at 50 mm from the geometric center. This behavior is maintained for all other similar cases. Another example is (G25-5-075) where it coincides with both (G25-4-100) and (G25-7-050) with both latter bolt patterns achieving less strength gain than (G25-5-075).

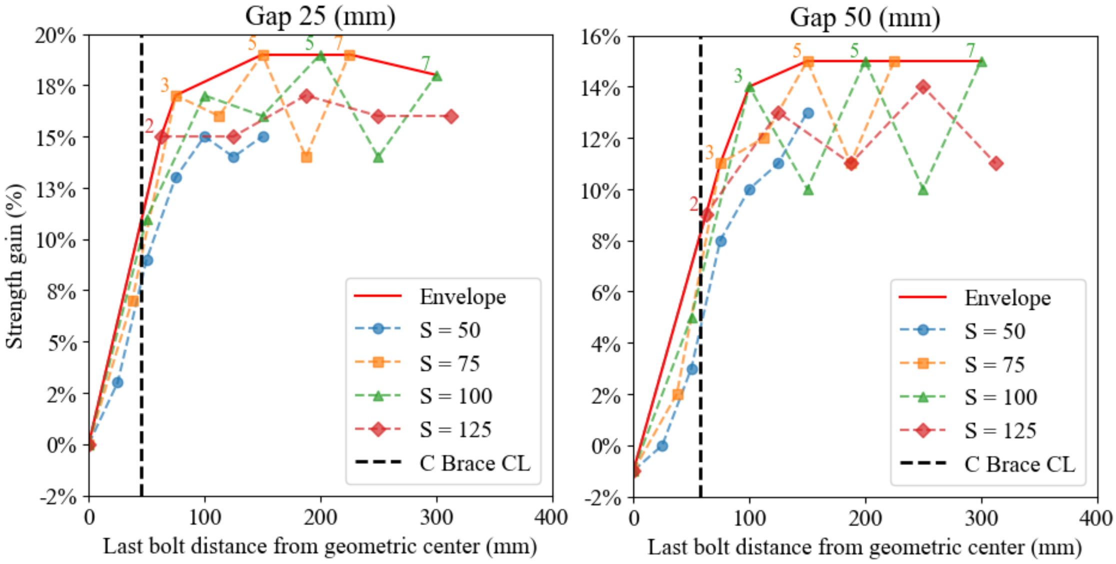


Figure 11 Strength gain vs strengthened zone length envelope for bolt patterns centered about geometric center.

Figure 12 shows the chord out-of-plane deformation for 3 specimens having the same strengthening zone length of 150 mm. The values shown are in mm, positive is for inwards deformation of chord walls (tension zone) and negative is for outwards deformation (compression zone). The deformed shapes in the Figure are magnified by scale of 5 to give clearer vision of the joints behavior. Both (G50-4-100) and (G50-7-50) are similar with the latter having an extra bolt between the two bolts on the compression side of (G50-4-100). It is noted that this has increased the strength of the joint. (G50-5-075) achieved higher strength gain than both.

The main difference is that the first bolt in the compression side is at 75mm from the geometric center while for both former patterns the first bolt was at 50mm which is closer to the tension zone. As Figure 12 shows for the cases where the bolt was at 50mm, the tension zone extended to reach the bolt where the bolt hole acted as a weakness zone in the joint, while for the case where the first bolt was at 75mm (G50-5-075), this effect decreased leading to a higher strength gain.

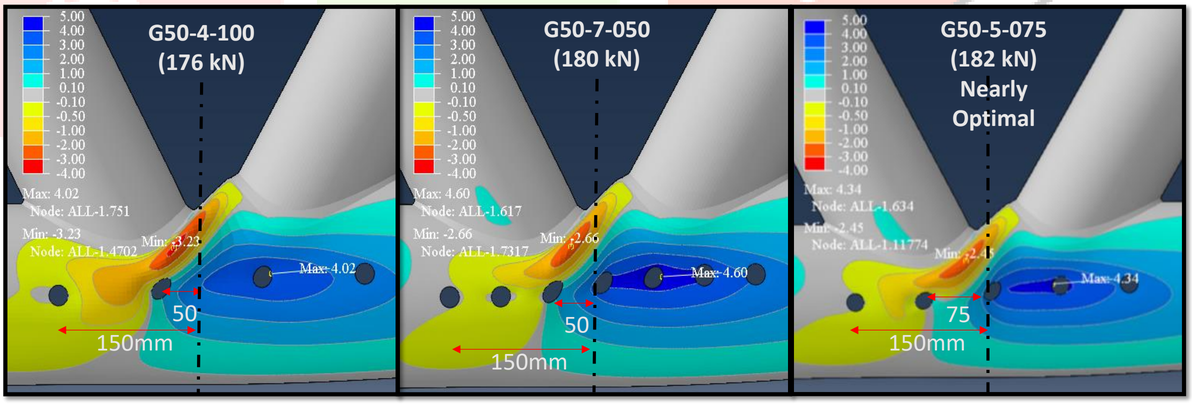


Figure 12 Out-of-plane deformation for specimens having similar strengthened zones but different bolts patterns

Furthermore, Figure 13 shows the out-of-plane deformation of the specimen at strength gain saturation for Gap 50mm joints (G50-3-100). The first bolt on the compression side became further from the tension zone (100 mm from the geometric center). The tension zone couldn’t reach the bolts on the compression side and the maximum strength gain was achieved using a single bolt on the compression side.

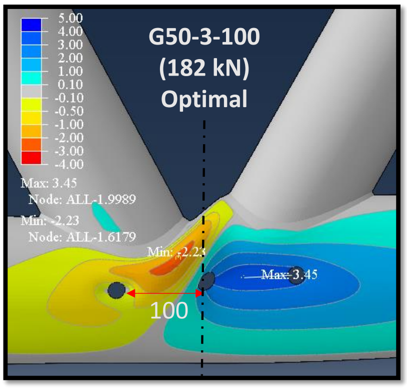


Figure 13 Out-of-plane deformation the specimen at strength gain saturation for Gap 50mm joints

Based on the observations in Figures (12 and 13), it can be noted that having the first bolt in the compression zone too close to the tension zone decreases the strength gain of the joint. To eliminate this effect and obtain a more uniform relationship, all the bolt patterns having bolts in that region were excluded. By studying Figures (11 and 12), it was determined that the zone to be excluded lies between the geometric center and the centerline of the compression brace. By excluding bolts in that region, a consistent relationship emerged, where the strength gain is mostly determined by the position of the first bolt on the compression side, regardless of the spacing or the number of bolts after the first bolt, as shown in Figure 14.

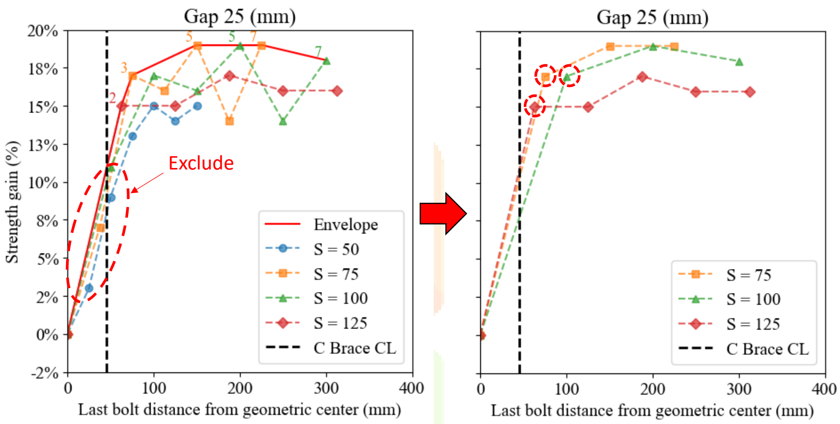


Figure 14 Length of strengthened zone and Strength gain relationship after removing bolts close to the tension zone.

IV. Conclusion

A rigorous Finite Element Modeling strategy was developed and validated against two independent experimental results to simulate overlapped and gapped K-joints strengthened by through bolts. A wide range parametric study examined the impact of various bolt patterns on the strength of K-joints using calibrated Finite Element Models (FEMs). A comprehensive research matrix comprising 110 specimens was meticulously designed to investigate the complex behavior of K-joints strengthened by different through-bolts patterns and different gaps shedding light on key insights.

- Through-bolts are more effective at strengthening gapped K-joints compared to overlapped K-joints.
- In overlapped K-joints, the strength gain from using through-bolts is directly proportional to the strengthened zone length.
- When strengthening gapped K-joints with multiple through-bolts, the pattern parameters (spacing, number of bolts) have less influence on strengthening behavior compared to the position of individual bolts within the pattern.
- Placing bolts at the geometric center of gapped K-joints has minimal impact on strength gain.
- For gapped K-joints, a significant portion of the maximum strength gain (at least 90%) can be achieved with bolt patterns that include a single bolt at a specific location on the compression side; additional bolts beyond this point have minimal effects on strength gain.
- Adding bolts close to the tension zone of K-joints negatively affects strength gain.

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