

Interface Bond Performance of Concrete-Filled Galvanized Steel Tubes Strengthened with Internal Circular Rings: A Taguchi–Grey Relational Study

Chethan Kumar S

Assistant Manager, Civil D&E, Jakson Green Limited, Bangalore, India

Sandesh NU

Department of Civil Engineering, B.M.S College of engineering, India

Anusha T.S

Assistant Manager, Civil D&E, Jakson Green Limited, Bangalore, India

Kumar N.S

Department of Civil Engineering, Ghouseia College of Engineering, Ramanagaram, India

Ashwini L.K

Department of Civil Engineering, Dr Ambedkar Institute of Technology, Bangalore, India

Syed Sharfuddin

Department of Civil Engineering, Ghouseia College of Engineering, Ramanagaram, India

Apsar Pasha

apsarpasha1982@gmail.com

Department of Physics, Ghouseia College of Engineering, Ramanagaram, India

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Abstract

Efficient transfer of longitudinal shear at the steel–concrete interface is required for composite action in concrete-filled steel tubular members, particularly near connections and other regions where load is introduced primarily through one component. This study evaluates the bond response of M40 concrete-filled galvanized steel tubes and quantifies the improvement produced by a single welded internal circular ring located near the top, middle, or bottom of the specimen. A Taguchi L9 orthogonal array was used to vary tube diameter (33.7, 42.2, and 48.3 mm), wall thickness (2.6, 3.2, and 4.0 mm), and length-to-diameter ratio (12, 14, and 16). Push-out tests were performed after 28 d of curing, and ultimate average bond stress was calculated from the peak load and nominal steel–concrete contact area. Unstrengthened specimens developed 0.878–1.899 MPa, whereas the top-, middle-, and bottom-ring series reached 1.86–2.85, 2.13–3.36, and 2.58–3.85 MPa, respectively. Relative to the unstrengthened series, the mean bond stress increased by 60.3% with a top ring, 85.6% with a middle ring, and 121.8% with a bottom ring. The bottom ring exceeded the middle and top positions by 19.5% and 38.4%, respectively, on a mean basis. For the top and middle positions, L/D produced the largest range in the response means; for the bottom position, diameter was dominant. Recalculated larger-is-better grey relational analysis identified $D = 42.2$ mm, $t = 4.0$ mm, and $L/D = 12$ as the best tested combination, while the factor-level optimum was $D = 48.3$ mm, $t = 4.0$ mm, and $L/D = 12$. The results demonstrate that ring position is a primary design variable because a ring close to the loaded end promotes mechanical interlock and mobilizes a larger resistance to core slip.

1. Introduction

The concrete-filled steel tubular (CFST) members are steel tubular members filled with concrete, which have been developed to integrate the tensile strength and confinement provided by the steel tube and the compressive strength provided by the concrete core. The interaction can defart local buckling of the steel shell, enhance the useable compressive strain of the concrete, and form a good structure for columns, bridge piers and other heavily loaded members [1, 2]. However, the benefits only come with proper force transfer between the two materials. The simultaneous loading of steel tube and concrete core may have a limited effect on the global capacity, but if the loading is mainly through the steel or concrete, the interface should transmit longitudinal shear to achieve full composite action [2, 3]. These happen at beam–column joints, column bases, splices, brackets and sudden changes in geometry.

The steel–concrete bond is usually said to be achieved by chemical bond, minute mechanical interlocking due to surface roughness, friction induced by radial pressure, and macro interlocking due to intentional connectors [3–6]. Chemical adhesion is gradually lost as slip occurs and thereafter friction and mechanical interlock take over. The bond response measured can then be influenced by tube size, diameter to thickness ratio, concrete strength and shrinkage, age of concrete, cross sectional shape, surface conditions of the inside of the tubes, and thermal history of the concrete [3–10]. Shrinkage causes the reduction of radial contact pressure and the loss of micro-interlocking, especially in large sections and smooth internal surfaces [3, 7].

Different enhancement methods have been studied such as expansive concrete, shear studs, internal ribs and welded rings. Expansive mixtures can be used to generate beneficial interface pressure, but they need to be considered from a long-term perspective due to shrinkage and restraint [4]. Studs and ribs are areas of bearing that are added but not part of the system and demand extra manufacturing. Internal rings are attractive due to the circumferential macro-interlock that they offer and have yielded greater bond augmentation than other stud configurations in previous push-out tests [3, 11]. Fewer papers have subsequently been written to verify that internal rings still work for large high strength circular tubes, and stainless-steel or other smooth surface systems [11–14].

In spite of this evidence, the position of one of the internal rings along the transfer length is not a variable that is commonly considered in the design. A ring located near the loaded end might intercept the advancing concrete core prior to development of large interface slip, and provide bearing before the large interface slip occurs, which might result in earlier mobilization of bearing; a ring placed in the middle or at a distance from the loaded end might alter the active transfer length and the stress distribution. The present study, therefore, compares the ring locations of the top, middle, and bottom ring in the same L9 geometric design. To achieve the above, the following were attempted: (i) establish the bond stress of unstrengthened M40 concrete-filled galvanized steel tubes; (ii) quantify the response to the three ring-locations; (iii) rank the influence of diameter, wall thickness and L/D based on Taguchi response means analysis; (iv) evaluate the available regression model for the unstrengthened series; and (v) conduct grey relational analysis for simultaneous optimization of the three responses to the three ring-locations with the direction of the larger is better.

2. Materials and Methods

2.1 Concrete and tube system

The specimens consisted of circular galvanized steel tubes with conventional M40 concrete. The Concrete proportioned as per IS 10262:2009 with water to cement ratio of 0.50. The reported quantities were 336kg/m³ of cement, 940kg/m³ of fine aggregate, 674kg/m³ of coarse aggregate and 168kg/m³ of water. The ratio of Cement: Fine Aggregate: Coarse Aggregate was 1:2.798:2.006 respectively. Three 150 mm cubes tested at 28 d developed compressive strengths of 41.87, 41.61, and 41.36 MPa, giving a mean of 41.61 MPa. The elastic modulus reported was 21,019 MPa. The values of the concrete properties used in the analysis are summarized in Table 1.

Table 1
Concrete mixture and reported hardened properties.

Property	Reported value	Unit / note
Concrete grade	M40	Conventional concrete
Cement	336	kg/m ³
Fine aggregate	940	kg/m ³
Coarse aggregate	674	kg/m ³
Water	168	kg/m ³
Water/cement ratio	0.50	by mass
28-d cube strength	41.61	MPa; mean of 41.87, 41.61, 41.36
Young's modulus	21,019	MPa (reported)

2.2 Experimental design and specimen geometry

Three levels and three factors Taguchi L9 orthogonal array was used. The nominal tube diameter D , the wall thickness t , and the length-to-diameter ratio of the specimen L/D were the control factors. The levels were $D = 33.7, 42.2$, and 48.3 mm; $t = 2.6, 3.2$, and 4.0 mm; and $L/D = 12, 14$, and 16 . The specimen length was determined from $L = D(L/D)$. For each geometric combination the test was conducted in two different ways: without a ring and with an otherwise identical ring placed at the bottom, middle, or top. So, there are 9 geometric combinations for every interface configuration.

Table 2
Taguchi L9 geometric design.

Run	D (mm)	t (mm)	L/D	Calculated L (mm)
1	33.7	2.6	12	404.4
2	33.7	3.2	14	471.8
3	33.7	4.0	16	539.2
4	42.2	2.6	14	590.8
5	42.2	3.2	16	675.2
6	42.2	4.0	12	506.4
7	48.3	2.6	16	772.8
8	48.3	3.2	12	579.6
9	48.3	4.0	14	676.2

2.3 Internal-ring fabrication and push-out testing

Circular steel plate rings were welded to the inner tube surface at one of three longitudinal positions: near the top, at the mid-height, or near the bottom. Figure 1 presents the source schematic, fabricated rings, an internal welded ring, and the specimen positioned in the universal testing machine (UTM). Concrete was placed after ring installation and the specimens were cured for 28 d. During the push-out test, axial compression was applied to the concrete core while the steel tube was supported, thereby producing relative slip and longitudinal interface shear. The peak load P_u was recorded for the unstrengthened, top-ring, and middle-ring series. The bottom-ring source table reported bond stress directly.

Figure 1. Specimen configuration and testing: (a) schematic of top, middle, and bottom ring positions; (b) fabricated circular rings; (c) ring welded to the internal tube surface; and (d) push-out specimen in the UTM. Images are retained from the source manuscript.

For reproducibility, the following source data should be supplemented before the journal is submitted: Outer diameter of the ring, clear opening, thickness of the plate, size and process of the weld, grade and yield strength of the steel, surface roughness of the internal surface, end clearances, loading rate, displacement instrumentation, and number of replicate specimens. The following parameters were not reported in the supplied manuscript and so they were not inferred.

2.4 Bond-stress calculation

The maximum average interface bond stress was determined as the maximum push-out load divided by the nominal steel–concrete contact area, which is the length of the transfer length.

$$\tau_u = P_u / (\pi DL) \quad (1)$$

where τ_u is the ultimate average bond stress (MPa), P_u is the peak push-out load (N), D is the nominal tube diameter (mm), and L is the specimen transfer length (mm). Substitution of the reported P_u , D , and L values reproduces the tabulated unstrengthened bond stresses; for example, Run 1 gives $76,000 / [\pi(33.7)(404.4)] = 1.77$ MPa.

2.5 Taguchi response analysis and regression assessment

The mean of the three L9 observations for each factor level k was used to calculate a mean at level k for each response. The factor effect was shown by the letter Δ which was the difference of the means between the maximum and minimum levels. A bigger Δ means a larger effect within the range of the investigated effect; it does not mean a statistically significant effect in the absence of replicated error estimates. The multiple linear regression provided was kept for the unstrengthen series:

$$\tau_u = 3.355 - 0.0605(D/t) - 0.1202(L/D) + 0.01097f'_c \quad (2)$$

Note

where f'_c is the 28-day concrete compressive strength in MPa. The quality of predictions was independently expressed in terms of R^2 , RMSE, MAE, and MAPE. Since all specimens are essentially the same concrete strength, the f'_c coefficient cannot be interpreted independently of this data set and the equation may be considered a in-sample geometric correlation, and not a general design model.

2.6 Corrected grey relational analysis

A geometry was explored using grey relational analysis (GRA) to find a geometry that worked for all three ring locations. Each response is normalized with the larger is better transformation, as higher bond stress is desired:

$$x_{ij} = [y_{ij} - \min(y_{ij})] / [\max(y_{ij}) - \min(y_{ij})] \quad (3)$$

where y_{ij} is the measured bond stress for run i and ring position j . The deviation from the ideal sequence is $\Delta_{ij} = |1 - x_{ij}|$. With a distinguishing coefficient $\zeta = 0.5$, the grey relational coefficient γ_{ij} and grade Γ_i are:

$$\gamma_{ij} = [\Delta_{min} + \zeta \Delta_{max}] / [\Delta_{ij} + \zeta \Delta_{max}]; \Gamma_i = (1/3) \sum \gamma_{ij} \quad (4)$$

The source manuscript had a directionally inverted normalisation that advocated for reduced bond stress. The reported GRA values in the following were therefore recalculated directly from the stresses supplied for the top, middle and bottom rings of the bonds, with the aid of the following equations: (3)–(4). Both the ranking of the runs and the factor-level optimum are altered by this correction.

3. Results

3.1 Unstrengthened CFGST response

The nine unstrengthened specimens gave an ultimate bond stress of between 0.878 and 1.899 MPa (Table 3) with an average value of 1.396 MPa. The lowest response occurred in Run 7 ($D = 48.3$ mm, $t = 2.6$ mm, $L/D = 16$), whereas the highest response occurred in Run 6 ($D = 42.2$ mm, $t = 4.0$ mm, $L/D = 12$). The range demonstrates that the effect of geometry was significant in changing the nominal interface resistance even though the concrete mixture and curing age were maintained constant.

Table 3
Unstrengthened CFGST push-out results and regression predictions (D and t in mm; P_u in kN; τ_u in MPa).

Run	D	t	L/D	P_u	Experimental τ_u	Predicted τ_u	Error
1	33.7	2.6	12	76	1.770	1.602	+ 9.5%
2	33.7	3.2	14	77	1.541	1.509	+ 2.1%
3	33.7	4.0	16	89	1.558	1.396	+ 10.4%
4	42.2	2.6	14	78	0.991	1.164	-17.5%
5	42.2	3.2	16	83	0.923	1.108	-20.0%
6	42.2	4.0	12	127	1.899	1.748	+ 8.0%
7	48.3	2.6	16	103	0.878	0.782	+ 10.9%
8	48.3	3.2	12	121	1.372	1.473	-7.4%
9	48.3	4.0	14	167	1.631	1.416	+ 13.2%

The regression had been as reasonably follows the experimental sequence as can be seen in the Fig. 2. The derived performance statistics were $R^2 = 0.819$, RMSE = 0.152 MPa, MAE = 0.143 MPa, and MAPE = 11.0%. When compared with the measured value, the absolute percentage error was between 2.1% (Run 2) and 20.0% (Run 5). The values are suitable for in-sample use as a summary and should not be viewed as the external validation of the equation as the same nine observations were used to obtain and validate the equation.

3.2 Geometric effects without internal rings

Table 4
Taguchi response means for unstrengthened CFGST bond stress (MPa).

Statistic	Diameter D	Thickness t	L/D
Level 1	1.623	1.213	1.680
Level 2	1.271	1.279	1.388
Level 3	1.294	1.696	1.120
Δ	0.352	0.483	0.561
Effect rank	3	2	1

The highest response range was obtained for L/D ($\Delta = 0.691$ MPa), wall thickness (0.458 MPa) and diameter (0.162 MPa). Importantly, the correct trend is a decrease in mean bond stress as L/D increases: 1.721 MPa at L/D = 12, 1.388 MPa at L/D = 14, and 1.030 MPa at L/D = 16. The original

manuscript talks of the other trend. A longer transfer length will lead to a larger nominal area in Eq. (1) and bond stress could be non-uniform and concentrated at the loaded end. The average response was not a monotonic function of the thickness t , but peaked at $t = 3.2$ mm. The unstrengthened series made only small response range in Diameter.

3.3 Effect of internal-ring position

All the internal-ring specimens performed better than the unstrengthened specimens (Table 5 and Fig. 4). The stresses in the top, middle and bottom of the rings ranged from 1.86 to 2.85 MPa, 2.13 to 3.36 MPa and 2.58 to 3.85 MPa, respectively. The bottom location yielded the greatest response in all nine combinations and the middle location was greater than the top location in each run. A comparison of the isolated maxima is a weaker argument for the position effect than this is.

Table 5
Bond stress (MPa) and improvement relative to the matching unstrengthened geometry.

Run	No ring	Top	Middle	Bottom	Top gain	Middle gain	Bottom gain
1	1.770	2.21	2.56	2.58	24.9%	44.6%	45.8%
2	1.541	2.07	2.37	2.99	34.3%	53.8%	94.0%
3	1.558	1.90	2.14	2.65	22.0%	37.4%	70.1%
4	0.991	2.02	2.37	2.90	103.8%	139.2%	192.6%
5	0.923	1.97	2.28	2.86	113.4%	147.0%	209.9%
6	1.899	2.85	3.36	3.49	50.1%	76.9%	83.8%
7	0.878	1.86	2.13	3.08	111.8%	142.6%	250.8%
8	1.372	2.72	3.15	3.85	98.3%	129.6%	180.6%
9	1.631	2.54	2.96	3.47	55.7%	81.5%	112.8%

This is because the average bond stress rose from 1.396 MPa without a ring to 2.238 MPa with a top ring, 2.591 MPa with a middle ring and 3.097 MPa with a bottom ring. These values are representative of gains of 60.3%, 85.6%, and 121.8%, respectively. When compared to the top location, the middle location was 15.8% higher, and the bottom location was 19.5% higher and 38.4% higher than the middle location. The original abstract showed significantly lower gains—these revised percentages are based on nine paired source observations.

3.4 Geometric effects for the ring-strengthened series

Table 6
Response means and factor effects for the three ring locations (bond stress in MPa).

Ring position	Factor	Level 1	Level 2	Level 3	Δ	Best level value
Top	D	2.060	2.280	2.373	0.313	48.3
Top	t	2.030	2.253	2.430	0.400	4
Top	L/D	2.593	2.210	1.910	0.683	12
Middle	D	2.357	2.670	2.747	0.390	48.3
Middle	t	2.353	2.600	2.820	0.467	4
Middle	L/D	3.023	2.567	2.183	0.840	12
Bottom	D	2.740	3.083	3.467	0.727	48.3
Bottom	t	2.853	3.233	3.203	0.380	3.2
Bottom	L/D	3.307	3.120	2.863	0.443	12

The most important parameter for both the top and middle ring was L/D, which yielded Δ of 0.683 MPa and 0.840 MPa, respectively. In both instances, mean bond stress decreased with increasing L/D, and increased diameter and wall thickness tended to enhance the response. The range (Δ) was the greatest for diameter (0.727 MPa), followed by L/D (0.443 MPa) and thickness (0.380 MPa) for the bottom ring. At the bottom ring, response increased monotonically with the diameter, with a maximum at L/D = 12 and a similar value at L/D = 4.0 for all positions.

3.5 Corrected multiresponse optimization

The corrected GRA ranks Run 6 first ($\Gamma = 0.879$), followed by Run 8 ($\Gamma = 0.846$) and Run 9 ($\Gamma = 0.615$). Run 6 combined D = 42.2 mm, t = 4.0 mm, and L/D = 12 and produced 2.85, 3.36, and 3.49 MPa for the top, middle, and bottom positions. Run 8 had the greatest bottom ring response (3.85MPa) and had modestly less top and middle ring response which gave it 2nd place in the equal-weight multiresponse ranking.

Table 7
Corrected larger-is-better grey relational coefficients, grades, and ranks.

Run	D	t	L/D	GRC top	GRC middle	GRC bottom	GRG	Rank
6	42.2	4.0	12	1.000	1.000	0.638	0.879	1
8	48.3	3.2	12	0.792	0.745	1.000	0.846	2
9	48.3	4.0	14	0.615	0.606	0.626	0.615	3
1	33.7	2.6	12	0.436	0.435	0.333	0.401	4
2	33.7	3.2	14	0.388	0.383	0.425	0.399	5
4	42.2	2.6	14	0.374	0.383	0.401	0.386	6
7	48.3	2.6	16	0.333	0.333	0.452	0.373	7
5	42.2	3.2	16	0.360	0.363	0.391	0.371	8
3	33.7	4.0	16	0.343	0.335	0.346	0.341	9

Table 8
Factor-level response of the corrected grey relational grade.

Factor	Level 1 GRG	Level 2 GRG	Level 3 GRG	Δ	Optimum value
Diameter D	0.380	0.545	0.611	0.231	48.3
Thickness t	0.387	0.539	0.612	0.225	4
L/D	0.709	0.467	0.362	0.347	12

Averaging GRG by factor level gives the factor-level optimum D3t3(L/D)1, corresponding to D = 48.3 mm, t = 4.0 mm, and L/D = 12. This combination was not one of the nine L9 runs, so it is a predicted optimum and requires a separate confirmation experiment. The largest GRG level range was associated with L/D (0.347), followed by diameter (0.231) and wall thickness (0.225; the latter two effects are similar). The ranking reinforces the importance of a short transfer-length ratio for simultaneously improving all three ring-location responses.

4. Discussion

4.1 Mechanism of bond enhancement

The systematic increase produced by the welded ring is consistent with a transition from a primarily adhesion–friction interface to a connector-assisted load-transfer mechanism. In an unstrengthened tube, chemical adhesion and micro-interlocking resist the initial load. Once local slip initiates, the available resistance depends on surface roughness, radial contact pressure, and friction. A circular ring interrupts the slip path and forces the concrete core to bear against the steel plate. The ring therefore

converts a portion of the longitudinal interface shear into localized bearing and confinement, producing macro-interlock [3, 11].

The superior bottom-ring response can be interpreted from the sequence of load transfer in the reported push-out setup. With the concrete core driven relative to the supported tube, a ring close to the loaded/support end is mobilized after a shorter slip-development length and can engage a larger confined concrete region before widespread interface degradation. A centrally located ring requires the shear flow to develop over a longer upstream interface, while a top ring is mobilized after still greater redistribution. The result is the observed ordering bottom > middle > top for all nine geometries. This explanation is mechanistic and consistent with the test arrangement, but direct load–slip curves and strain measurements are required to separate adhesion, friction, and ring bearing quantitatively.

4.2 Interaction with diameter, thickness, and L/D

The dominant L/D effect in the top & middle ring series is the result of both the nominal stress definition, and the nonuniformity of shear at the interfaces. In Eq. (1) it is assumed that the peak load is uniformly distributed over πDL . In actual push-out specimens, shear is focused around particular connectors and close to the loaded end. The calculated average bond stress is going to be less as L increases; this is because the denominator is increasing but not necessarily the numerator, P_u (the bond stress). In previous studies of CFST [2, 3, 8, 14] similar sensitivity to interface length and member size has been reported. The increase in wall thickness generally had a positive effect on the ring-strengthened response as the stiffer tube is able to resist local radial dilation and is more capable of generating bearing at the welded plate. In the unstrengthen series, there was little effect from diameter, but in the bottom rings, it was dominant. The change implies an interaction between the circumference, confinement and connector bearing. The bigger the diameter the longer the perimeter of the ring and the bigger the potential bearing interface, but the larger the nominal contact area too. The currently available data cannot separate the contribution of $D \times t$ or $D \times (L/D)$ interaction effects as these are aliased by the L_9 design.

4.3 Comparison with previous research

The effect of internal rings observed is consistent with the larger body of the CFST literature. Tao et al. [3] had described normal interfaces, studs, expansive concrete, and internal rings as the bond-enhancement measures tested, with the former being the least effective, the latter as the most effective and internal rings being in between. Similarly, Dong et al. [11] found high ring effectiveness in large specimens of high strength circular CFST. Research has found that ribs or rings are helpful for such smooth steel surfaces to increase mechanical interlock at the interfaces between the steel and the surrounding concrete, especially for stainless-steel interfaces [12, 13]. The present contribution builds on that knowledge by demonstrating that the longitudinal position of a single ring is not neutral: the mean bond stress increased from 2.238MPa when the ring was moved up to 3.097MPa when the ring was moved down, under the push-out arrangement adopted. The unstrengthen values are also in the wide range of experimental variations reported in small circular push-out CFST specimens, whose bond

strength can be a function of size, shrinkage, age and surface condition [3, 5, 8, 14]. Care must be taken not to make direct comparisons, since many of the literature deals with carbon or stainless steel, whereas the present ones are made with galvanized steel.

4.4 Reliability and design interpretation

Use of regression model for a useful interpolation of the nine unstrengthened observations, but $R^2 = 0.819$ is not to be interpreted as evidence of general predictive reliability. The model has several coefficients which are relative to a small number of data, the value of concrete strength is fairly constant and there isn't any independent validation set. Furthermore the negative L/D coefficient reflects the mean trend, at only 3 separate levels. Replicated tests would be needed over a wider range of tube size, concrete strength, surface condition, and ring geometry, with external validation and uncertainty bounds, to make it a more defensible design model. The same should be applied to the corrected GRA. It does not give a structural design equation, it gives a transparent equal weight ranking of the three ring positions. Run 6 is the optimum that was observed in the best way to do it, while D3t3(L/D)1 is a projected factor level optimum. Confirmation testing is necessary since Taguchi main-effect predictions are based on limited interaction and because the optimum combination was not included in the original L9 array.

4.5 Limitations

There are no reported replicate testing or dispersion, load–slip curves, residual bond stress, failure-mode photographs following testing, tube strain measurements, surface roughness or steel mechanical properties data and no complete ring/weld dimensions. The Taguchi ranges can be used as sensitivity indicators, but do not enable formal significance statements in the absence of replicate error. Local shear concentrations are also concealed by the use of nominal average bond stress. Finally, the specimens are small compared to many structural CFST columns, and so size effects and connection scale load transfer must be considered for extrapolation to design.

5. Conclusions

Within the reported materials, dimensions, and push-out configuration, the following conclusions are supported:

- The bond stress at failure for unstrengthened M40 CFGST specimens ranged from 0.878 to 1.899 MPa with the average values being 1.396 MPa.
- All tested geometries showed an improvement in bond stress with a welded internal circular ring. The mean increases from the matched unstrengthened specimens were 60.3%, 85.6%, and 121.8% for the top, middle, and bottom rings, respectively.
- Ring position produced a consistent ordering across all nine L9 runs: bottom > middle > top. The bottom position exceeded the middle and top positions by 19.5% and 38.4%, respectively, on a mean basis.

- For unstrengthened, top-ring, and middle-ring specimens, L/D produced the largest response range. Bond stress decreased as L/D increased from 12 to 16. For bottom-ring specimens, diameter was the dominant factor, followed by L/D and wall thickness.
- The supplied unstrengthened regression yielded $R^2 = 0.819$, RMSE = 0.152 MPa, MAE = 0.143 MPa, and MAPE = 11.0%. It should be used only as an in-sample correlation until validated with independent data.
- Corrected larger-is-better GRA identified Run 6 ($D = 42.2$ mm, $t = 4.0$ mm, $L/D = 12$) as the best tested multiresponse combination. The factor-level optimum was $D = 48.3$ mm, $t = 4.0$ mm, $L/D = 12$ and requires confirmation testing.
- The improvement is attributed to circumferential mechanical interlock and localized bearing at the welded ring. Complete load–slip and strain measurements are needed to quantify the contribution of adhesion, friction, confinement, and ring bearing

Declarations

Author Contribution

Chethan Kumar S: Conceptualization, Methodology, Writing – Original Draft. Sandesh N U: Data Curation, Formal Analysis. Anusha T S: Software, Writing – Review & Editing. N S Kumar: Review and Editing. Ashwini L K: Validation of Data. Syed Sharfuddin: Formal Analysis, Data Curation. Apsar Pasha: Conceptualization, Review and Editing. All authors have read and agreed to the published version of the manuscript

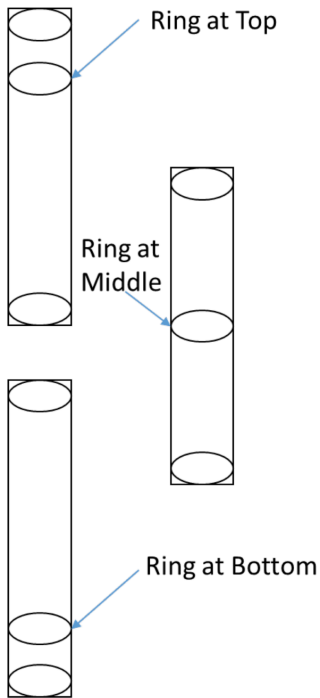
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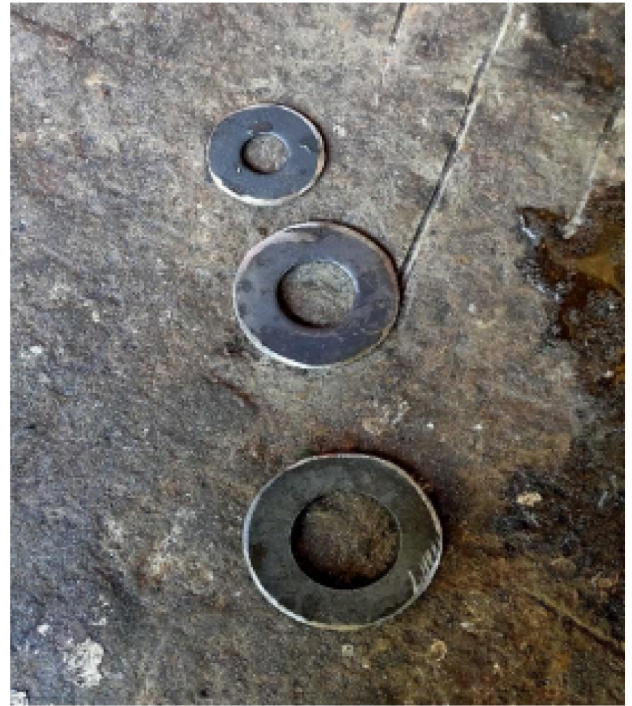
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Figures

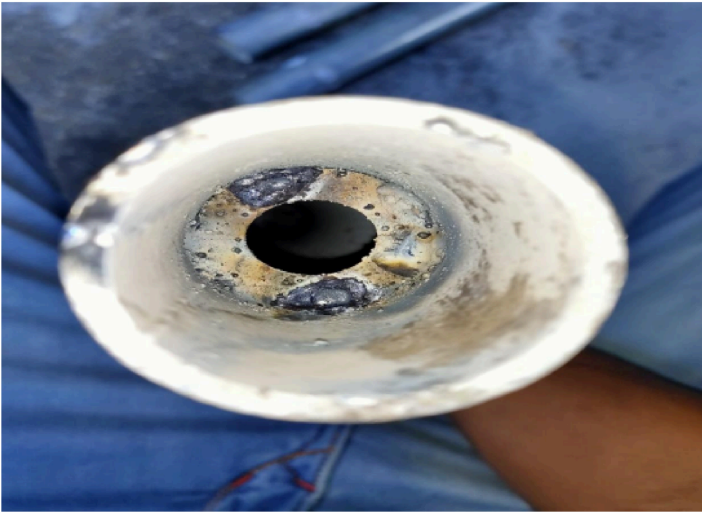
(a) Ring-location schematic



(b) Fabricated circular rings



(c) Ring welded inside tube



(d) Push-out test in UTM



Figure 1

Specimen configuration and testing: (a) schematic of top, middle, and bottom ring positions; (b) fabricated circular rings; (c) ring welded to the internal tube surface; and (d) push-out specimen in the UTM. Images are retained from the source manuscript.

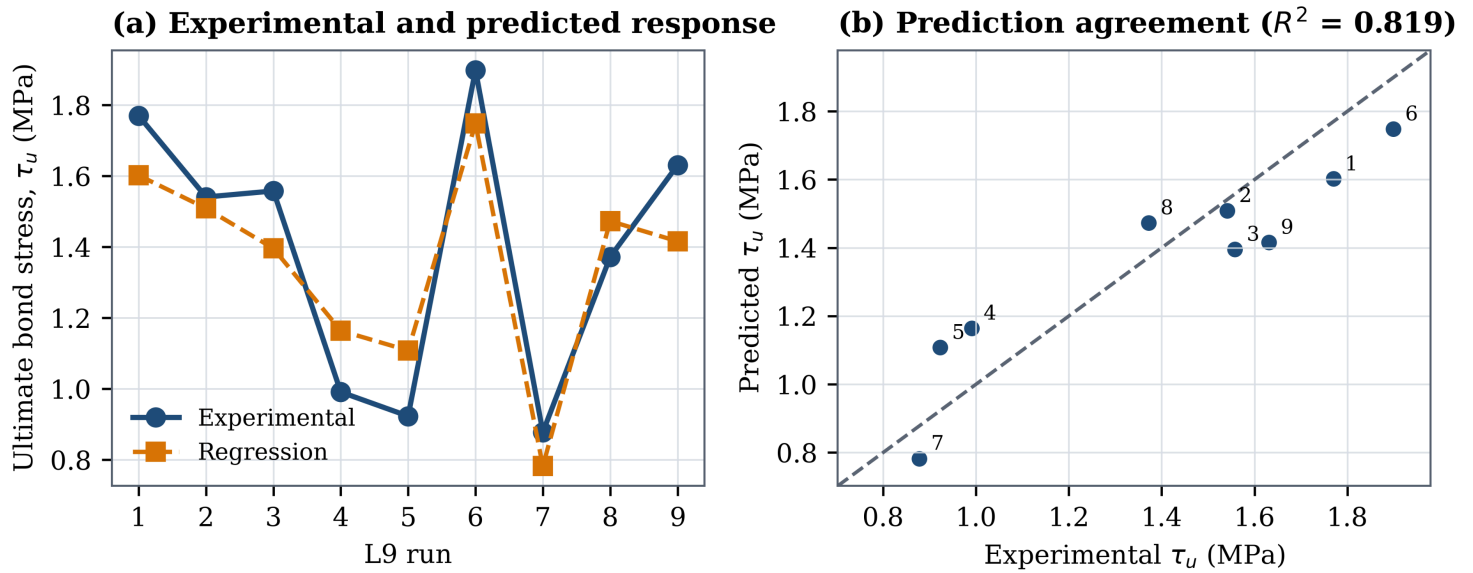


Figure 2

Regression assessment for the unstrengthened M40 CFGST series: (a) experimental and predicted bond stress across the L9 runs and (b) predicted versus experimental values.

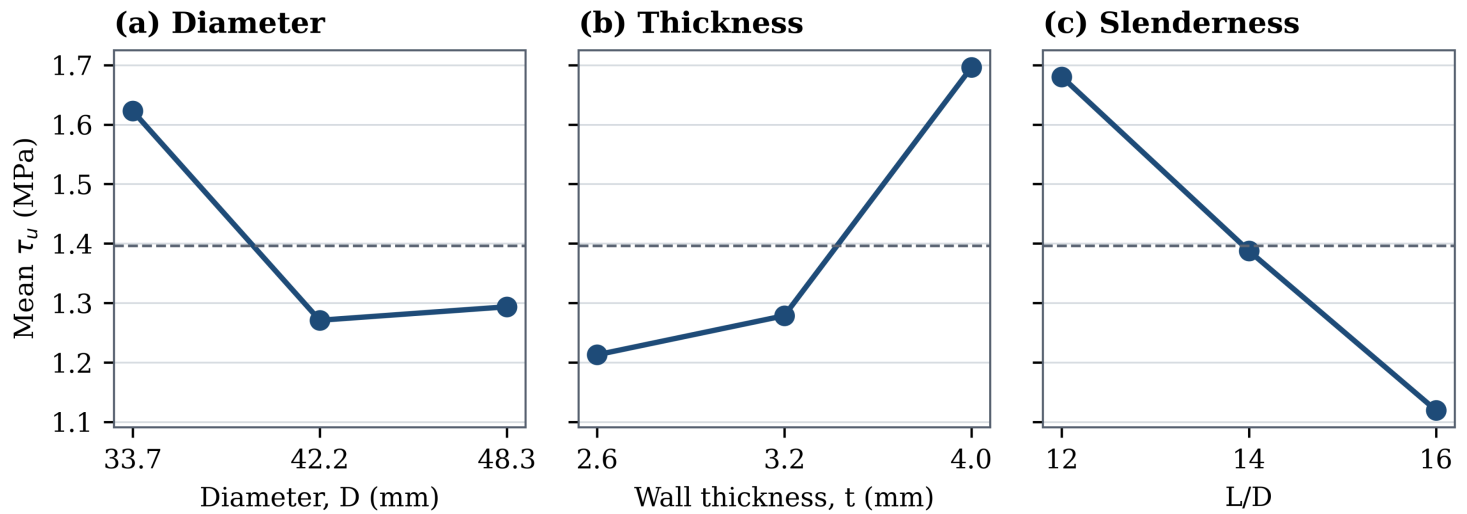


Figure 3

Main effects of (a) diameter, (b) wall thickness, and (c) L/D on the mean bond stress of unstrengthened CFGST specimens. The dashed line is the overall mean.

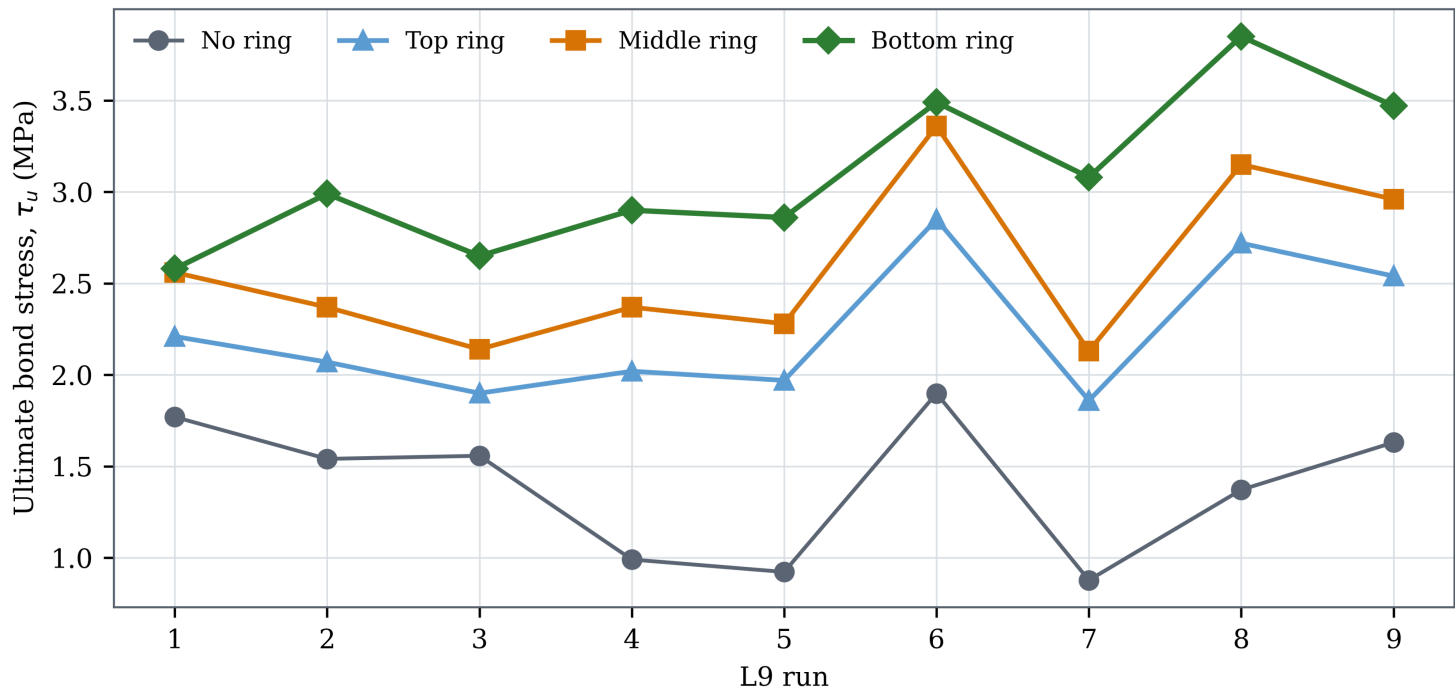


Figure 4

Ultimate bond stress for the unstrengthened and three ring-location series across the L9 geometries.

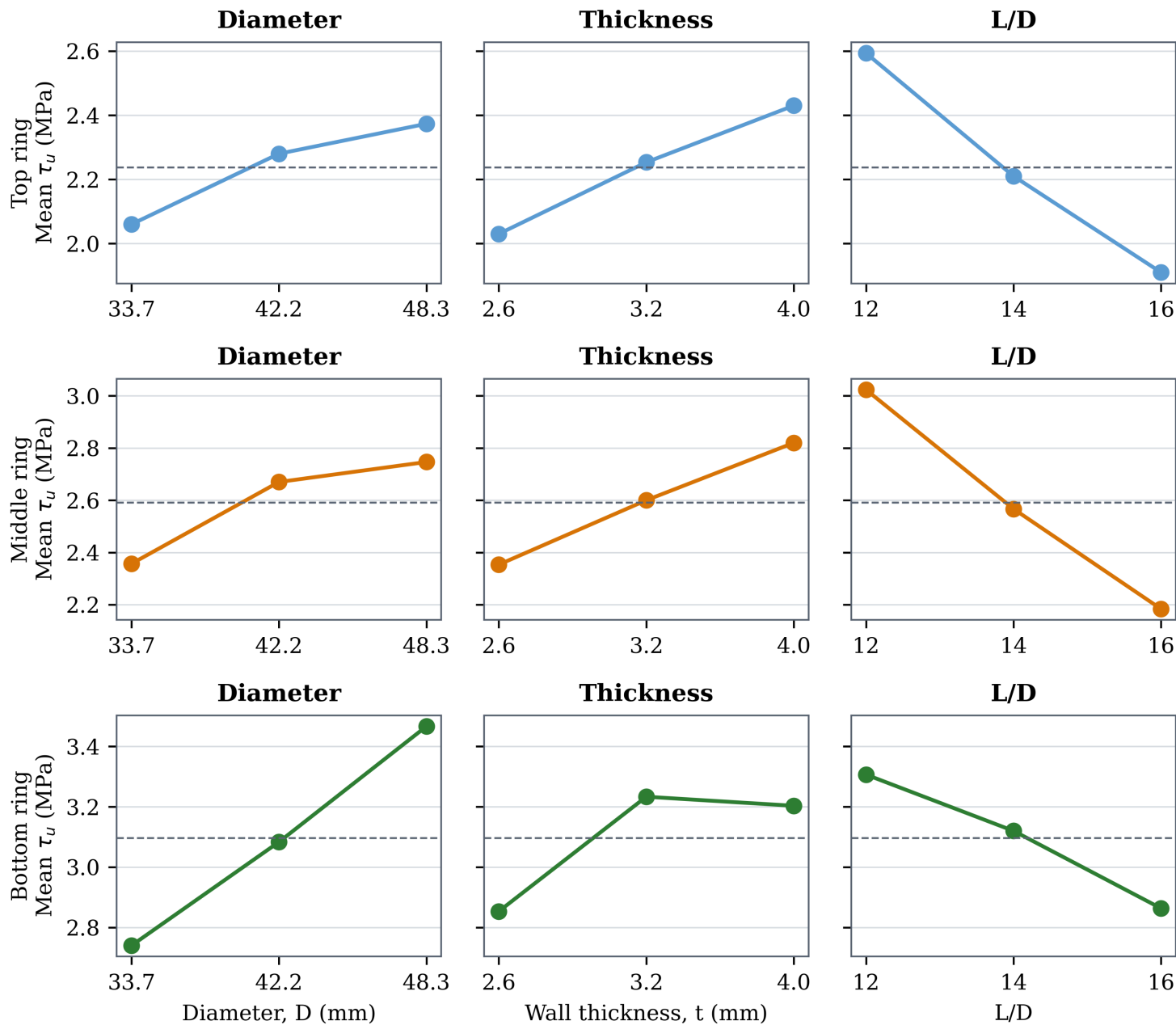


Figure 5

Main-effect plots for top-, middle-, and bottom-ring configurations. Dashed lines indicate the position-specific overall mean.

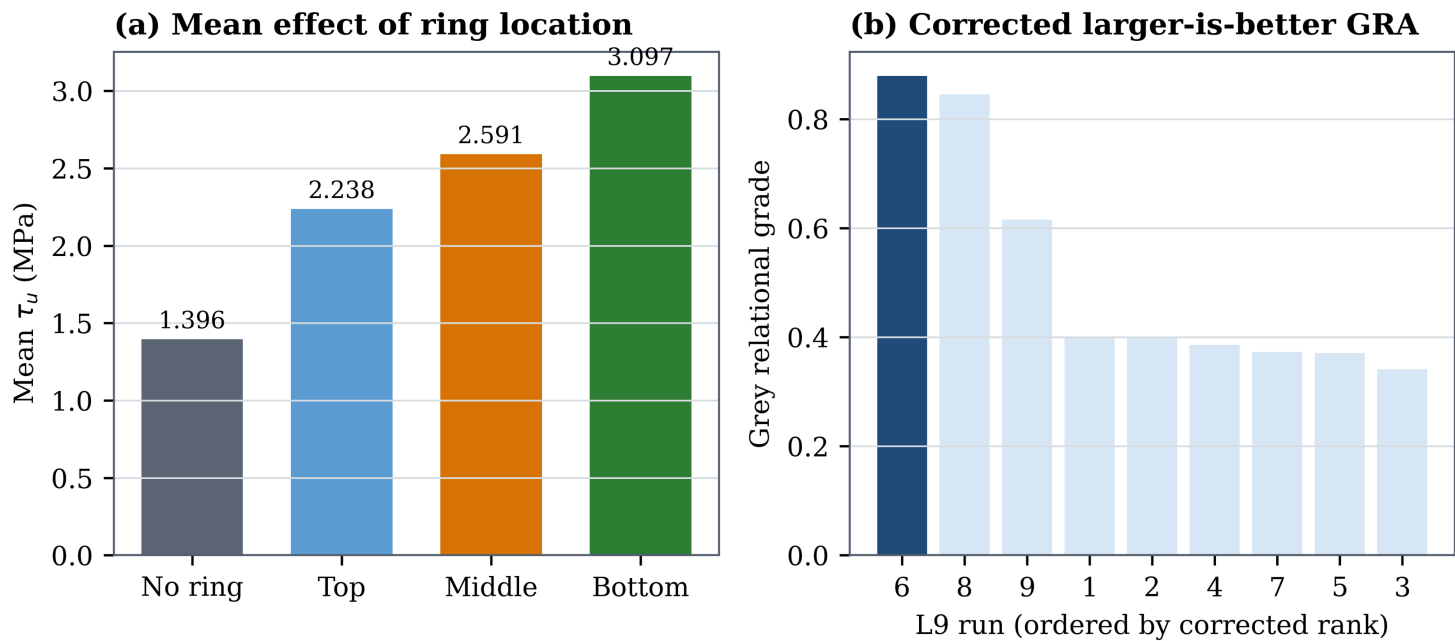


Figure 6

(a) Mean bond stress for each interface configuration and (b) corrected equal-weight grey relational grade. The highlighted bar is the best tested multiresponse configuration.