Optimization of Bolted Connection in Steel Corbel Attach to RC Column of MRT Viaduct

Yazmin Sahol Hamid¹, Hazrina Mansor¹, Amir Atif Abdul Razak¹, Haikal Ajmal Bin Bukhory¹ and Nursafarina Ahmad¹

¹ School of Civil Engineering, College of Engineering, Universiti Teknologi MARA (UiTM), Shah Alam 40450, Malaysia
Corresponding author: yazminsahol@uitm.edu.my

Abstract. MRT is one of the backbones of a city's public transportation system, capable of carrying large crowds. The use of a portal frame in the design of an MRT train station has raised significant concerns about how the portal frame's load will be supported by the extended structure element known as a corbel. A corbel is a protruding structural element that supports weights like primary beams and girders. Engineers must then decide how to properly bolt the steel corbel structure to the concrete pier segment or columns. Generally, most corbel structure designs were constructed of concrete; however, in this study corbel design was made of steel so that the steel portal frame could rest on the corbel structure, allowing for more usable area on the platform, such as kiosks and other amenities. Optimization of end plate thickness and beam web thickness is carried out. Manual calculations are used in addition to FEA modeling to examine the bolt's deflection, shear, bearing, tension, slip, and block tearing resistance. When using Eurocode, all three loadings, transverse force, vertical force, and transverse moment, produce values that are 10% lower than the British Standard. As a result, designers can optimize their designs using Eurocode.

1. Introduction
MRT is the country’s largest infrastructure project, requiring massive tunnelling, underground construction, and viaduct work. If everyone drove, the city would be congested therefore this type of rail transportation system in Kuala Lumpur is expected to help alleviate traffic congestion as more people use public transportation in the Klang Valley.

Corbels structure usually consist of a Segment Box Girders, crossheads, bridge decks, piers, etc. It also serves as a support for important beams and girders and is a component of the MRT structure. However, it has been found out that there is less research on corbel particularly on bolted connection. Aside from the technical difficulties of designing and building a complex rail structure, the design of the corbel structure for the Mass Rapid Transit 2 (MRT 2) train station is fraught with problems and difficulties. Because of the sophisticated design of the architects, problems arose regarding how to support the load of the portal frame itself. To support the portal frame, they needed an extended structure element known as a corbel. Corbel is a protruding structure from the column face that is used substantially in supporting primary beams and girder [1]. Figure 1 shows a SketchUp drawing of the steel corbel structure supporting the extended portal frame. Figures 2(a) and (b) illustrate the actual steel corbel structure installation at the Damansara Damai construction site, as well as a close-up view of the steel corbel structure. It is designed to be installed outside of the existing platform to accommodate other platform elements like information kiosks and shop spaces. Unfortunately,
engineers must decide the optimum bolt-type connection to be employed with sufficient strength to link the steel corbel structure to the concrete pier column, which is a concern and a challenge. The goal of this research is to better understand how steel corbels behave and how they are connected. This research focuses on existing MRT projects that use steel corbels attached to concrete pier segments rather than concrete corbels.

![Illustration of corbel structure supporting load from portal frame.](image)

**Figure 1.** Illustration of corbel structure supporting load from portal frame.

![Steel corbel structure at Damansara Damai: (a) Installation of steel corbel, (b) close up view of steel corbel.](image)

**Figure 2.** Steel corbel structure at Damansara Damai: (a) Installation of steel corbel, (b) close up view of steel corbel.

In this study the steel corbel connections are designed and analyzed using StaadPro V8i in line with Eurocode 3: Design of Steel Structures. The aims of this study are to optimize steel corbel bolted connections in terms of bolt numbers and size, end plate and beam web thickness. To determine the adequacy of the connection calculation of the connection's shear, bearing, tension, slip, and block tearing resistance is conducted and checked in accordance with Eurocode 3: Design of steel structures Part 1-8. Joint Design. Lastly, to analyze the stress distribution from the modelling outcome and recommend the optimum design is based on Joints in Steel Construction: Moment-Resisting Joints to Eurocode 3, Tata Steel UK 2011. Generally, these safety checks are crucial during initial construction, including corbel installation, temporary bolting, bracket and seating alignments, and supported element construction. The corbel structure design can be optimized by providing an economical design while maintaining connection strength. In conclusion, if the structural engineer underestimates the design force that the connection must withstand, a failure can occur.

1.1. Corbel

Corbels are often constructed to withstand vertical loads at the beam's end, but concrete corbel also support horizontal forces caused by creep, temperature changes, and shrinkage, which are as important [2]. The vertical load carrying capability of concrete corbel structures was found to be significantly
reduced due to horizontal forces operating on the corbel, yet the corbel was nevertheless harmed due to horizontal limitations, according to a test conducted by the Portland Cement Association [1].

Steel corbels are manufactured off-site, away from the impact of site employees and weather [3]. Therefore, the environmental factor is reduced. Steel, unlike concrete, does not creep, shrink, or degrade when properly protected. Speed, site safety, lifespan, fire prevention, built-in quality, aesthetics, and sustainability are just a few of the benefits of steel corbels. Reinforced concrete corbels, on the other hand, need up to 28 days to cure before being used, whereas steel corbels can be used almost immediately once bolts are installed [4]. According to [1], the aesthetic and architectural manifestations of the steel corbel were important considerations in the selection as the use of steel corbels can reduce waste from formwork and abortive activities on the construction site.

Generally, most corbels structure designs were constructed of concrete; however, in this study corbel design was made of steel so that the steel portal frame could rest on the corbel structure, allowing for more usable area on the platform, such as kiosks and other amenities. The worry engineers had was how to build the most optimized steel corbel structure based on the number of bolts, moreover the majority of the design was done using a design software and no 2nd order analysis was done, plus validation was done using manual calculations. Besides that, it is a fact that failure due to a connection is the most serious as it can cause failure to the entire structure.

1.2. Steel Corbel Connections

Steel corbels are made up of several elements, as shown in figure 3, including an I-beam as the main structure, stiffeners, end plates, and bolts for connection to piers, portals, or columns [5]. I-beam that carry loads will experience bending, shear and deflection. The shear resistance of a beam depends on the shear capacity or shear buckling resistance. If the shear forces do not exceed 60% of the shear capacity, the shear effect on the bending capacity is considered low and can be ignored. However, if the shear loads exceed 60% of the shear capacity, the shear effect must be considered when calculating the moment capacity [6].

Structural failure can take various forms, but failure due to a connection is the most serious, and this is the type of failure that can occur in steel corbel constructions. The number of bolts is one of the parameters that affect the quality and durability of a bolted joint connection when it comes to maximizing its efficiency under load [7–10]. One element in bolt application is the insert bolted connection, which is utilized in grip joints as an additional friction purpose and is subjected to compressive force due to bolt preload. When estimating the strip mass per bolt, the thickness of the connecting strip and the distance between bolts should be assumed [7]. This can be done by dividing the external loads with the mass of the resulting joint. Thus, the joint efficiency, or load carrying capability per unit mass, may be calculated.

![Figure 3. Steel corbel.](image-url)
2. Finite element modelling process

In this study, the I-Beam section property of Advance UKB 686x154x170 has been proposed to be used. All dimensions were according to the actual dimension of the corbel structure as listed in Table 1. The proposed type of bolt that was used in the connection of the corbel structure was grade 8.8 M24, which shows the diameter of the bolt to be 0.024m. The corbel structural elements, i.e., web section, flange section, stiffeners, end plate section, and bolt structure are all steel. Support reactions were assigned only to the bolt structure's beam elements. To provide fixed support, it was necessary to restrain axial loading in the directions of the X, Y, and Z axes. It is assumed that the strength of concrete is equal to 4400 kN/m². The portal frame model shown in Figure 4 utilized in this study was produced by a group of students that competed in the MSSA-CIDB Open Ideas Competition (OIC) for the year 2018 (MSSA-CIDB OIC 2018) with the theme "REIMAGINE: MRT Stations," and has been remodeled using StaadPro software (see figure 5) to determine the maximum loading of the portal frame structure.

![Figure 4. Portal frame structure.](image)

| Element       | Section (see Figure 2) | Thickness / Diameter (m) | Length (m) | Width (m) | Shape   |
|---------------|------------------------|--------------------------|------------|-----------|---------|
| Plate         | Flange A and B         | 0.0237                   | 1.346      | 0.356     | Rectangle |
|               | Flange C               | 0.0237                   | 0.800      | 0.356     | Rectangle |
|               | Web A                  | 0.0145                   | 1.362      | 0.696     | Rectangle |
|               | Web B                  | 0.0145                   | 0.800      | 0.602     | Rectangle |
|               | Stiffener              | 0.0150                   | 0.275      | 0.275     | Triangle  |
|               | End plate              | 0.042                    | 1.820      | 0.430     | Rectangle |
| Beam          | Bolt                   | 0.024                    | 0.800      | -         | Circle   |

![Figure 5. Structural design model of the MRT 2 train station comprises of portal frame section.](image)
2.1. Proposed variation parameters

Four parameters were considered in this study to determine the best design of the steel corbel. The four parameters that have been proposed are bolts design arrangement configuration, diameters of bolts, dimensions of the endplates and web thickness of the beam.

2.1.1. Configuration of bolts design arrangement. The configuration of 24 numbers of bolts represents the original design proposed by the engineer. It is critical to optimize to ensure that the most effective or functional optimize strength is used for the bolted connection of the steel corbel structure. That is why the numbers of bolts, the thickness of the plate, and the beam web are also modelled with various sizes and thicknesses to achieve the most optimal size. In this study there are four (4) configuration sets of bolt number analysed in this work. The four configuration sets were described in the following paragraphs.

i) Configuration set 1: 24 number of bolts (original design by the design engineer)

The bolts in the top part of the corbel are created first followed by the bolts at the bottom parts. The equal amounts of bolts (12 number of bolts) were placed at both of the top and bottom part of the plate which gives a total of 24 number of bolts as per original design by the design engineers at the consultant firm.

ii) Configuration set 2: 18 number of bolts

The second configurations were proposed whereby the bolts were reduced to 10 number of bolts (upper) and 8 number of bolts (lower).

iii) Configuration set 3: 14 number of bolts

Next, for the third configuration of bolt arrangements, the bolts were reduced to 8 number of bolts (upper) and 6 number of bolts (lower).

iv) Configuration set 4: 10 number of bolts

The 4th configuration were arranged so that the bolts were reduced to 6 number of bolts (upper) and 4 number of bolts (lower).

The bolts are modelled with four different diameter sizes (16mm, 20mm, and 24mm), the end plates with three different thicknesses (15mm, 20mm, and 25mm), and the beam webs with three different thicknesses (11mm, 13mm, and 15.4mm).

2.1.2. Boundary conditions and loads applied. Corbel was supported on a concrete pier via steel bolt. Therefore, it is crucial to get an accurate value of bolt-concrete stiffness behavior. This is done by considering having fixed support at bolt end. Meanwhile, pinned supports were assigned at the middle nodes of each bolt which is in X-axis and Y-axis only.

Ulrike Kuhlmann, Frantisek Wald, and Jan Hofmann [11] conducted an experiment to determine how different concrete strengths affect the stiffness of the concrete under varying displacements. The point of zero displacement is regarded to be the point of failure. As illustrated in Figure 6, the lesser the displacement, the greater the stiffness of the concrete. Ulrike et al. [11] discovered that the optimal stiffness of concrete occurs at 1.5mm displacement, and the MRT project used a 35MPa concrete grade for the pier. Thus, we may deduce the stiffness value from the graph, which is 4300 N/mm. As a result, this value will be utilized to determine the stiffness of the X- and Y-axes.

This study used a linear static analysis to establish the maximum value of the support reactions studied using EC, and it was discovered that the transverse force, vertical force, and transverse moment were 128 kN, 523 kN, and 459 kNm, respectively.
3. Validation of FEM Modelling
The vertical deflection of the steel corbel generated by StaadPro was compared against manual calculation. For the FEM, the taken point was at Node 56 and the vertical deflection values in Y-axis was considered. The analysis results comparison between StaadPro and theoretical calculations were presented in table 2.

| Load (kN) | StaadPro Results (mm) | Theoretical Calculations (mm) | % Difference |
|-----------|------------------------|-------------------------------|--------------|
| 100       | 1.793                  | 1.49                          | 14.81        |
| 200       | 3.009                  | 2.98                          | 0.96         |
| 300       | 4.226                  | 4.47                          | 5.46         |
| 400       | 5.442                  | 5.95                          | 8.54         |
| 523       | 6.938                  | 7.79                          | 10.94        |
| 700       | 9.090                  | 10.42                         | 12.76        |

It can be concluded that the difference between theoretical calculation and StaadPro results was very close and thus the modelling is validated and accepted.

Sensitivity analysis was also conducted to discover the ideal mesh sizes and computation effort. The study used mesh sizes of 5mm to 30mm. Beyond a mesh size of 10, the deflection values become nearly constant. The study used a 10-mesh size to reduce computing load.

4. Results and Analysis
Table 3 summarizes the outcomes of the bolt analysis results. From the study it was found that both 18 bolts and 24 bolts design are satisfactory, but for optimization purpose, 18 bolts design can be selected.

4.1. Verification of StaadPro analysis results with EC3
Based on Eurocode 3: Design of Steel Structures - Part 1-8: Design of Joints Detail, a hand calculation on bolt design was performed. Firstly, the clearance and bolt positioning are checked in terms of bolt clearance, bolt positioning, maximum end and edge distance, and minimum and maximum spacing. Second, the bolts are tested against several aspects, which are shear resistance, bearing resistance, tension resistance, and slip resistance. Third, in order to ensure the end plate is adequate to resist shearing force on it, its capacity is tested in terms of shear resistance (gross and net section), shear resistance of web and block tearing. From The results it was found that all bolt numbers passed the clearance and bolt positioning check.
Table 3. Summary of bolt analysis results.

| Bolt Number | 10 upper | 14 lower | 18 upper | 6 lower | 10 upper | 8 lower | 12 upper | 12 lower |
|-------------|----------|----------|----------|---------|----------|---------|----------|----------|
| Highest Stress Value (N/mm²) | 559 | 386 | 517 | 358 | 348 | 221 | 334 | 212 |
| Corbel Yield Stress (N/mm²) | 355 | 355 | 355 | 355 | 355 | 355 | 355 |
| Comparison with Yield Stress | Over | Over | Over | Over | Under | Under | Under | Under |
| Design Acceptance | Unsatisfactory | Unsatisfactory | Satisfactory | Satisfactory |

Table 4 displays the shear resistance of bolts of various sizes. The values shaded in grey boxes represented insufficient shear resistance. For 16mm bolt sizes, all 10 nos., 14 nos., and 18 nos. of bolts are insufficient to resist the design shear of 651kN, whereas only 10 nos. of bolts are insufficient for 20mm bolt sizes. Aside from that, the checking is adequate.

Table 4. Shear resistance of bolts: Shear resistance (Required Value: 651kN).

| Bolt sizes / Bolt numbers | 16mm | 20mm | 24mm |
|---------------------------|------|------|------|
| 10 nos.                   | 301.4kN | 470.4kN | 677.8kN |
| 14 nos.                   | 422.0kN | 658.6kN | 949.9kN |
| 18 nos.                   | 542.5kN | 846.7kN | 1220.0kN |
| 24 nos.                   | 723.4kN | 1129.0kN | 1626.7kN |

The results of bearing resistance design for various bolt sizes are shown in Table 5. According to the table, all bolt configurations were adequate to resist the required value of 651kN, and the checking was satisfactory.

Table 5. Bearing resistance of bolts: Bearing resistance (Required Value: 651kN).

| Bolt sizes / Bolt numbers | 16mm | 20mm | 24mm |
|---------------------------|------|------|------|
| 10 nos.                   | 1328kN | 1660kN | 1992.0kN |
| 14 nos.                   | 1859.2kN | 2324kN | 2788.8kN |
| 18 nos.                   | 2390.4kN | 2988kN | 3585.6kN |
| 24 nos.                   | 3187.2kN | 3984kN | 4780.8kN |

Table 6 displays the tension resistance results for bolts with diameters of 16mm, 20mm, and 24mm. The configurations of 10 and 14 bolts for the 16mm diameter bolt are insufficient to resist the required value of 651kN. Aside from the aforementioned, the checking is adequate.

Table 7 shows the slip resistance design results, which show that nearly half of the bolt configurations were insufficient to meet the required slip resistance value of 651kN. According to the table, the configurations with 18 and 24 numbers of 20 mm and 24mm diameter bolts were the only ones that could withstand the slip resistance capacity of 651kN. As a result, such configurations are the fewest that can be used to optimize the corbel design.

Table 8 shows a summary of the shear (gross and net section) and block resistance design for various end plate thicknesses. It can be concluded that all plate thickness configurations passed the testing, and thus a 15mm plate can be chosen to optimize the design.
Table 7. Slip resistance of bolts: Slip resistance (Required Value: 651kN).

| Bolt sizes / Bolt numbers | 16mm  | 20mm  | 24mm  |
|---------------------------|-------|-------|-------|
| 10 nos.                   | 452.2kN | 705.6kN | 1016.7kN |
| 14 nos.                   | 633.0kN | 987.8kN | 1423.4kN |
| 18 nos.                   | 813.9kN | 1270.1kN | 1830.1kN |
| 24 nos.                   | 1085.2kN | 1693.4kN | 2440.1kN |

Table 8. Checking of end plates: Checking of End Plates (Required Value: 651kN).

| Plate Thickness | Shear Resistance (Gross Section) | Shear Resistance (Net Section) | Block Tearing |
|----------------|---------------------------------|--------------------------------|---------------|
| 15mm           | 1706.5kN                        | 2202.41kN                      | 2644.4kN      |
| 20mm           | 2275.3kN                        | 2936.5kN                       | 3525.8kN      |
| 25mm           | 2844.1kN                        | 3670.7kN                       | 4407.3kN      |

Table 9 summarizes the local shear resistance for different web thicknesses. The web must carry a value of 651kN. All web thickness configurations passed the design check, and thus 11.0mm plate can be chosen to optimize the design. Table 10 shows the optimum parameter values that can be used to optimize the design of the corbel structure.

Table 10. Optimized corbel structure design.

| Parameters                | Selected value |
|---------------------------|----------------|
| Bolt numbers              | 18 nos.        |
| Bolt sizes                | 20mm           |
| End plated thickness      | 15.0mm         |
| Beam web thickness        | 11.0mm         |

4.2. Optimized corbel structure design

Figure 7 displays the original corbel bolt location with 24 bolt numbers. To make a bolt with 18 bolt numbers, six bolts that are designated with a red circle must be removed.
5. Summary and conclusions

Through this research, all of the research objectives have been completed. Using the four specified parameters, optimization of the bolted connection was achieved. The four parameters considered are 1) Configuration of the numbers of bolts 2) Diameter of the bolts 3) Plate thickness and 4) Web thickness. The numerical analysis of the optimization of bolted connections in steel corbels attached to RC columns of the MRT viaduct revealed several suggestions for optimizing the connections. The suggestions are as follows:

- Comparing Eurocode with British Standard for loading analysis. This was determined using portal frame modeling and Eurocode requirements. When utilizing Eurocode as a reference, all three loadings, transverse force, vertical force, and transverse moment, generate 10% lower values than the British Standard. As a result, designers can use Eurocode to optimize their designs.
- By optimizing the steel corbel's bolted connection, the total number of bolts required can be reduced from 24 to 18. The diameter of the bolts can be adjusted from 24mm to 18mm, and the end plates' thickness from 25mm to 15mm. The beam's web thickness can also be reduced from 15.4mm to 11mm. There were no problems resisting the design loads mentioned.
- The connection's sufficiency against shear, bearing, tension, slide, and block tearing was checked manually. The stress distribution produced by StaadPro finite element modeling was also analyzed to establish the ideal steel corbel design. The contour of the stress distribution was determined using FEA modeling results. In summary, FEA modeling and manual calculations in accordance with applicable rules of practice show that steel corbel structures can be adjusted to be more cost effective while still resisting design loads.

6. References

[1] Kriz L B and Raths C H 1965 Connections in Precast Concrete Structures-Strength of Corbels, PCI J. 10 1 16–61
[2] Boon C W, Ooi L H, Tan J G and Goh C Y 2020 Deep excavation of an underground metro station in karstic limestone: a case history in the Klang Valley SSP Line, Geotech. Sustain. Infrastruct. Dev. 423–430
[3] Bjorhovde R, Brozzetti J and Colson A 1987 Connections in Steel Structures: Behaviour, Strength & Design (Amsterdam: Elsevier Applied Science) pp 1-394
[4] Dai X, Lam D, Sheehan T, Yang J and Zhou K 2018 Use of bolted shear connectors in composite construction 12th International Conference on Advances in Steel-Concrete Composite Structures (ASCCS 2018) (Valencia)

[5] Joints in Steel Construction 2013 Moment-Resisting Joints to Eurocode 3 (P398) (Berkshire: The Steel Construction Institute and The British Constructional Steelwork Association)

[6] Eurocode 3 2005 Design of steel structures - Part 1-8: Design of joints (Brussels: European Committee for Standardization)

[7] Bianchi G, Aglietti G, and Richardson G 2007 Optimization of bolted joints connecting honeycomb panels 1st CEAS, 10th European Conference on Spacecraft Structures, Materials and Mechanical Testing (Berlin)

[8] Thomsen O 1997 Sandwich Plates with ‘Through-the-Thickness’ and ‘Fully-Potted’ inserts: Evaluation of Differences in Structural Performance, Compos. Struct. 40 159–174

[9] Thomsen O and Rits W 1998 Analysis and design of sandwich plates with inserts: a high-order sandwich plate theory approach, Compos. Part B-engineering 29 795–807

[10] Ericksen W S 1960 The bending of a circular sandwich plate under normal load (Washington: Air Force-Navy-Civil Subcommittee)

[11] Kuhlmann U Wald F and Hofmann J 2014 Design of Steel-to-Concrete Joints. Design Manual II (Prague: Publishing House of CTU)

Acknowledgments

The authors would like to acknowledge The Institute of Research Management and Innovation (IRMI) UiTM, Shah Alam, Selangor, Malaysia and Ministry of Higher Education (MOHE) for the financial support of this research. This research is supported by MOHE under the Fundamental Research Grant Scheme (FRGS-RACER) with project code: 600-IRMI/FRGS-RACER 5/3 (060/2019).