Dissertation Summary

Title: Topology Optimisation of Beam-to-Column Joints for Additive Manufacturing

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Abstract:

Additive manufacturing (AM) as a fundamental part of the automated manufacturing procedures, has the potential to reshape the construction industry. Hence, this research dissertation was carried out, aimed at promoting wider application of AM in construction. The focus of this study was placed on the topology optimisation of steel beam-to-column joints and the assessment of the structural performance of the optimised joints. During the research, the influence of the topology optimisation setups was explored through comparison of the selected structural performance variables between the benchmark joint and the optimised joints.

1. Introduction

Additive manufacturing has been applied to a variety of industries, such as automotive and aerospace manufacturing industries. Because of the size limits, surface toughness limits and the lack of understanding of the underlying material properties, the application of AM in the construction industry falls behind other industries (Laghi et al., 2020; Tolosa et al., 2010; Williams et al., 2016; Wu et al., 2016). The lack of relevant standards also prevents wider application of AM in construction.

This research project is aimed at investigating the structural performance of beam-to-column joints, which was optimised by means of topology optimisation. These joints were optimised by linear topology optimisation. To achieve the full advantage of optimisation, these joints were predetermined to be fabricated by wire and arc additive manufacturing (WAAM).

According to the flow chart in Figure. 1, in this research, two topology optimisation analyses and one nonlinear analysis were conducted in Abaqus (Dassault Systèmes Corp., 2021). The pre-analysis was performed to demonstrate the effect of the optimisation configurations. Based on the results from the pre-analysis, the formal analysis was subsequently conducted. After postprocessing the optimised results in the formal analysis, the nonlinear analysis, incorporating both geometric and material nonlinearities, was carried out to further demonstrate the influence of the optimisation configurations on the structural performance of the optimised joints. The introduction of the optimisation models and the discussion of the optimisation results are described in Section 2, while the introduction to the nonlinear analysis and the discussion of the nonlinear analysis results are described in Section 3 and 4. In Section 5, the conclusions from the present study are summarised.

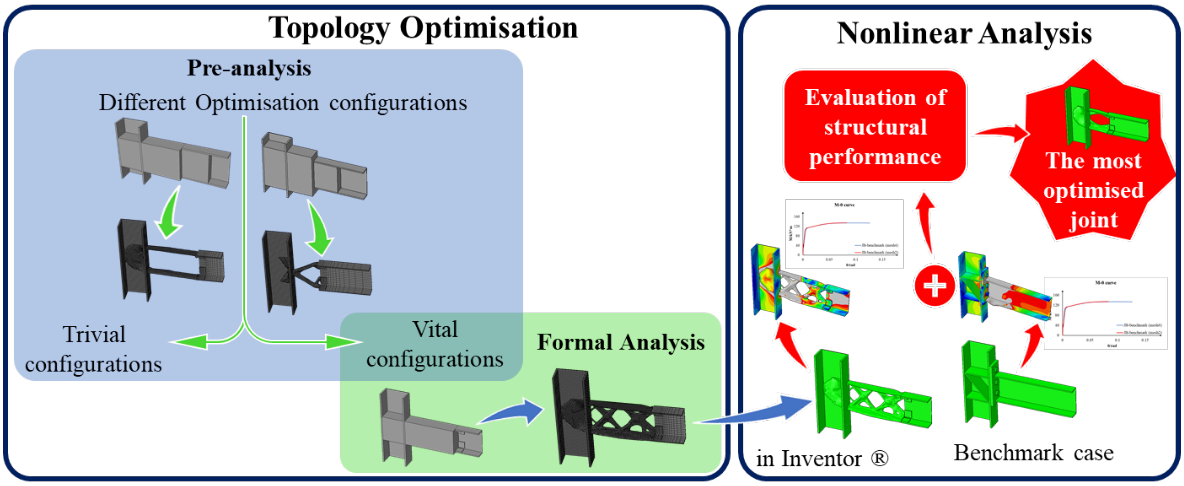


Figure. 1 Flow chart of this research project

2. Topology Optimisation of Beam-To-Column Joints

The beam-to-column joint (Figure. 2), subjected to optimisation, is located at the 1st and 2nd floor level of a steel moment-resisting frame. A series of finite element models established in Abaqus for linear topology optimisation. Different design domain configurations were considered, which can affect the optimised shape of this joint. These configurations included the inclusion of column stiffeners, the mesh size, the loading cases (single loading case and multiple loading case), the optimisation target (η_c), and the dimension of design domain (l_c, L_c, H_c) (Figure. 2).

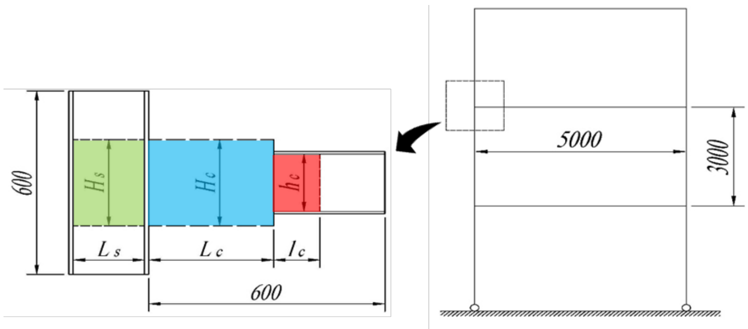


Figure. 2 Position of beam-to-column joints and dimensions of design domain

By qualitative assessment, the influence of these configurations was investigated and is described in Section 2.3. By this assessment, these setups are classified into two categories, the trivial influence factors and the vital influence factors. The variation of the trivial factors, such as l_c, was shown to have minor influence on the optimised shape of the design domains, while the variation of the vital ones, such as L_c and H_c, led to significant change of the optimised shape. The influence of different design domain configurations was evaluated quantitatively in the subsequent nonlinear analyses.

3. Nonlinear Analysis of Benchmark and Optimised Joints

To quantitatively assess the structural performance of these optimised domains, nonlinear analysis of these optimised joints was conducted as described in Section 3 and the nonlinear analysis results are described in Section 4. To reflect the practical requirements, the extended end-plate beam-to-column joint was selected as the benchmark case (Figure. 3). The optimised geometry was further refined using Inventor (Autodesk Inc., 2021), as shown in Figure. 4. The useless material was removed from the as-optimised geometry in the refining process, to reduce the element amount in the finite element models. The refined optimised geometry was then reimported into Abaqus to form the models in the nonlinear analysis.

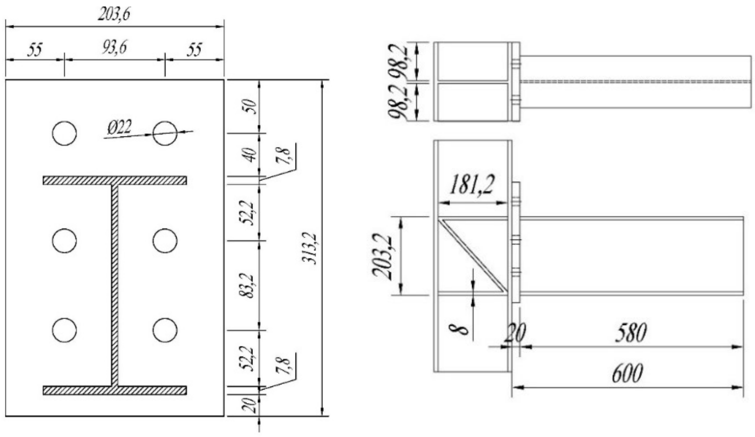
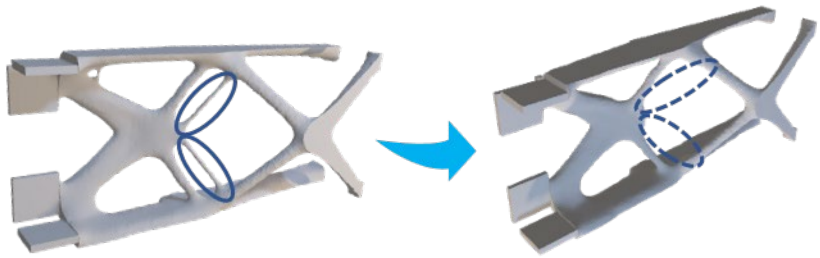


Figure. 3 Dimensions of benchmark joint



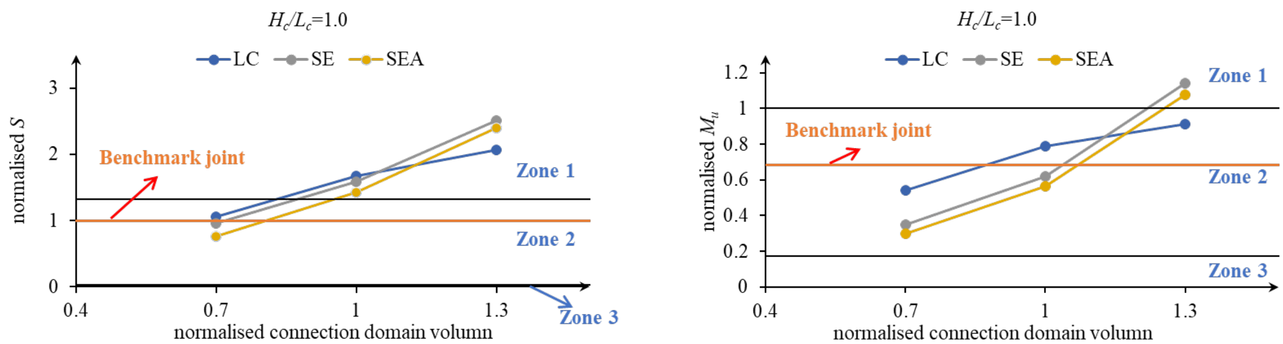
As-optimised geometry from Abaqus Refined optimised geometry from Inventor

Figure. 4 Example of as-optimised and refined geometry

4. Comparisons Between Benchmark and Optimised Joints

In Section 4, the assessment of the structural performances is made based on five structural performance variables, including the rotation stiffness (S), the bending moment (M_y) and rotation angle (θ_y) at yield point, bending moment capacity (M_u) and rotation capacity (θ_u). Some vital findings in this research are described in Figure. 5 and 6. Regardless of the variation of weights in multiple loading cases (LC case, SE case, SEA case), S, M_u, and θ_u increase with the increase in connection domain volume (blue part in Figure. 2). The variation of these weights can cause a larger variation in θ_u, while this variation leads to a trivial impact on S. Hence, optimising these weights may be a worth-trying stargate to promote joint ductility.

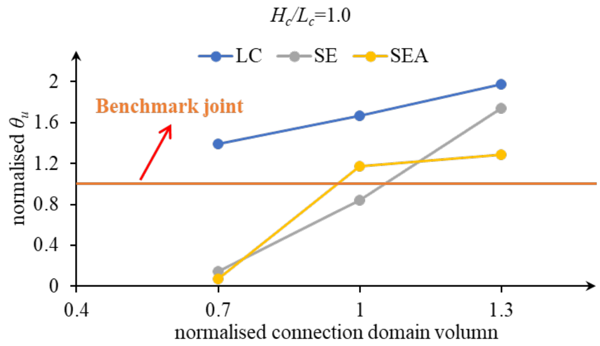
Through assessment and comparison with the benchmark case, the most outstanding optimised joint, named FJ-1013C-LC (H_c/L_c=1.0, normalised connection design domain=1.3), was found (Figure. 5 and 6), as this joint has the largest ductility with sufficient rotation stiffness and moment capacity (Figure. 7). Further refinement of the optimised results and realisation of the optimised joints are currently underway.



(a) (b)

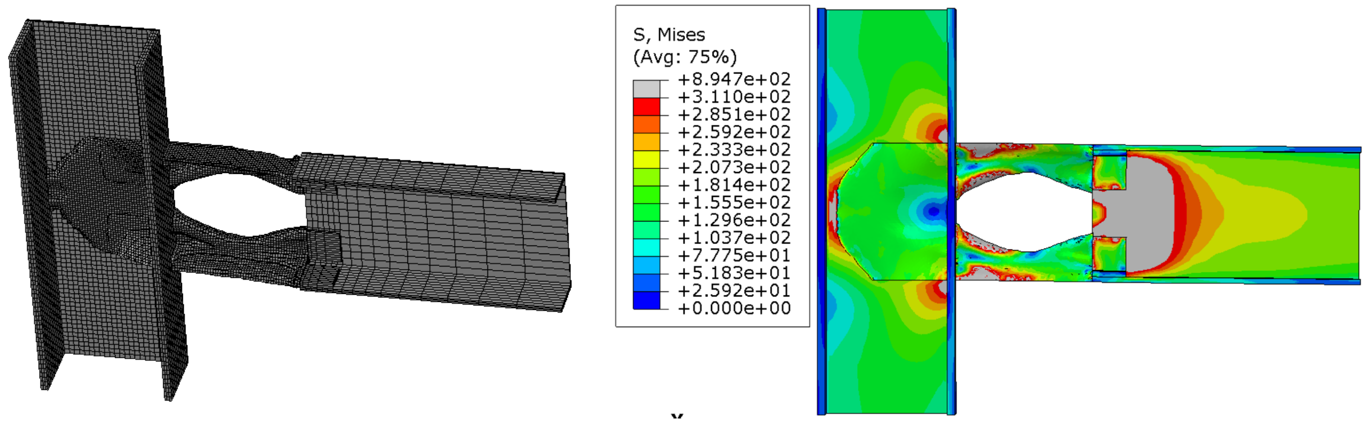
Figure. 5 The variation in the (a)S and (b)M_u along with the variation of the connection domain volume at different height-to-length ratios (H_c/L_c)

Note: In (a), Zone 1, 2 and 3 are the rigid joint zone, semi-rigid joint zone, and nominally pinned joint zone respectively. In (b), Zone 1, 2 and 3 are the full-strength joint zone, partial-strength joint zone, and nominally pinned joint zone respectively



(c)

Figure. 6 The variation in the θ_u along with the variation of the connection domain volume at different height-to-length ratios (H_c/L_c)



(a) (b)

Figure. 7 (a) The linear topology optimisation result and (b) the nonlinear analysis result of FJ-1013C-LC

5. Conclusions

After the present study, the impact of optimisation configurations on both the optimised geometry of design domain and the structural performance of optimised joints is assessed preliminarily. By the assessment, two strategies to promote the optimised joints were concluded. The first strategy is optimising joints under multiple loading cases and optimising the weights of these loading cases. Another strategy is changing the length (L_c) and height (H_c) of the blue domain (Figure. 2) and the optimisation target. The efficiency of these strategies are currently underway.

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