Design of Efficient Steel Trusses to Resist Progressive Collapse

Nada Elkady(1) , Yasser Eljajeh(2), Kevin Gilsenan(3) , Levingshan Augusthus Nelson(4)

(1) Graduate Engineer (Renaissance Associates Ltd) and PhD Student (Salford University), (2) Principal Engineer (Renaissance Associates Ltd), (3) Director (Renaissance Associates Ltd), (4) Lecturer Civil Engineering (Salford University)

1.0 Introduction

Viadux II is one of the most challenging current projects in Manchester. Due to the level of complexity associated with this project, innovative solutions were essential in the design process.

The overall Viadux development includes the construction of a 39-storey residential tower, 15 storey office building, a connecting podium structure, and the conversion of a Grade II listed masonry Viaduct. The proposed buildings are to be built over the existing Viaduct structure that dates from the late 1870's which was constructed as part of Manchester Central Station.

This case study discusses the challenges faced during the design process of the office building's transfer truss, shown in Figure 1.1.

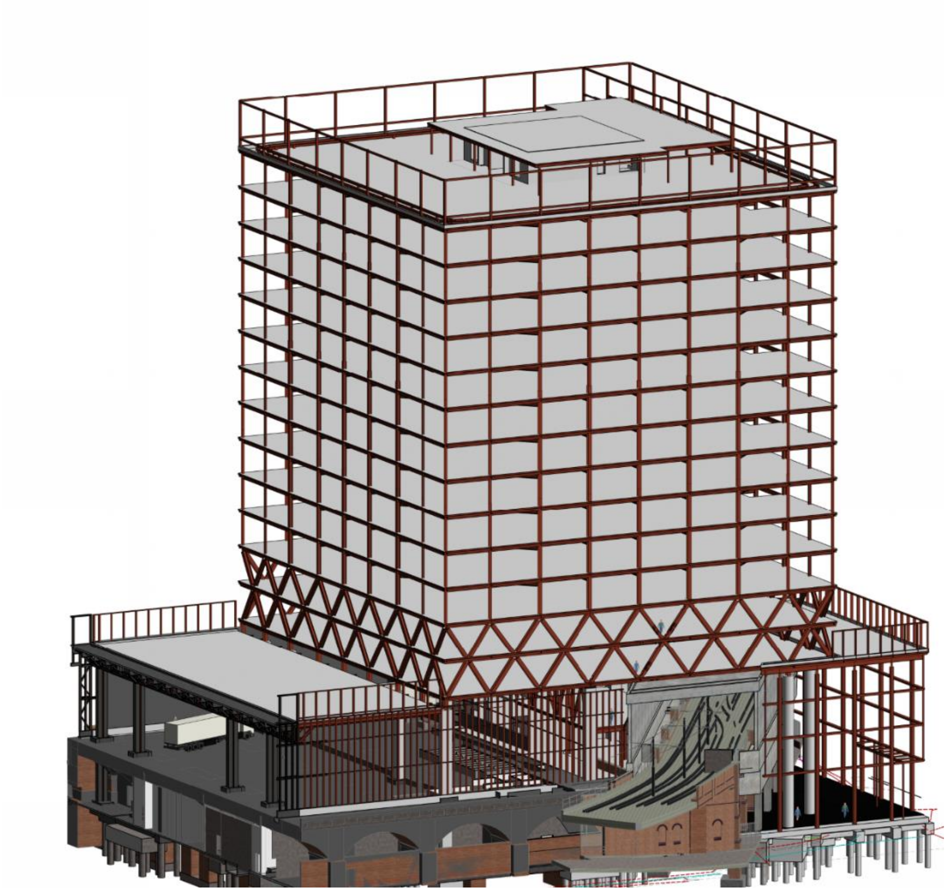

Figure 1.1 Phase II (Block C) of Viadux Development

Given the fact that the project is being constructed on top of a Grade II listed viaduct, minimal penetrations had to be achieved by reducing the number of columns supporting the building. Another restriction to the locations of these columns is the tram line crossing the site from its southwest to the northeast. Thus, with the limitations in mind, 10 columns with up to 34.5m spans were strategically placed. Due to the large spans, a transfer truss was needed to help transfer the loads from the structure's 15 storeys to the columns, making it a crucial aspect of the structure's load-bearing system. In addition to the reduced number of columns, the required access of HGVs to Manchester Central Service Yard dramatically increases the risk of progressive collapse of the entire structure. The risks associated with this building and other high-risk structures can be effectively mitigated by the proposed state-of-the-art solutions.

2.0 Progressive Collapse Framework

The initial step to design the transfer truss against progressive collapse was to look into the current Eurocode guidance on the issue. It was concluded that the Eurocode guidance on progressive collapse design for high-risk structures is extremely limited, overlooking aspects such as preventing against cliff-edge scenarios (a risk associated with key element design), providing recommendations for the structural analysis process and identifying failure criteria. Thus, Renaissance's design team, which includes experts in dynamics, progressive collapse and historic structures, in collaboration with researchers from Salford University, decided to develop a framework for progressive collapse design that can be applied to this project while also being highly adaptable to a wide range of high-risk projects. This framework, presented in Figure 2.1, compiles guidance from research and international codes including:

- BS EN 1990:2002 +A1:2005 Basis of Structural Design +UK NA
- BS EN 1991-1-7:2006+A1:2014 General Actions-Accidental Actions
- General Services Administration (GSA): Alternative Path Analysis & Design Guidelines for Progressive Collapse Resistance 2016
- ASCE/SEI 41-13: Seismic Evaluation and Retrofit of Existing Buildings

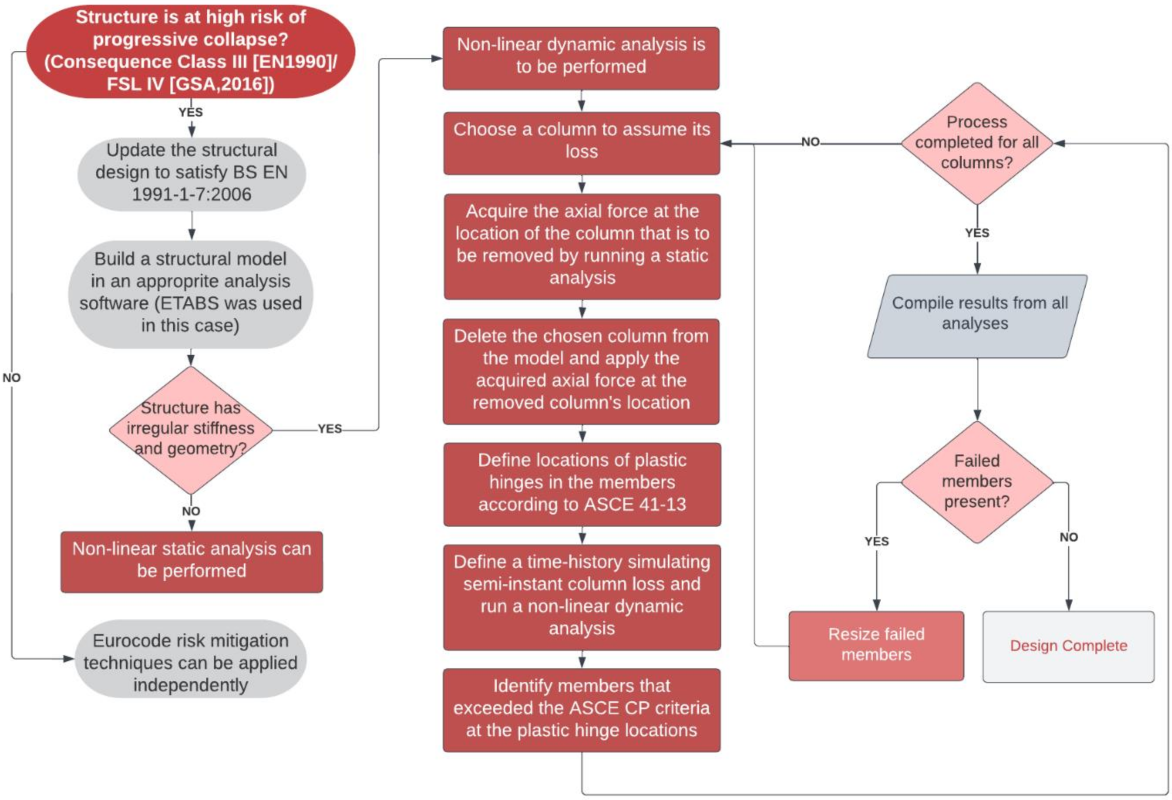

Figure 2.1- Proposed Progressive Collapse Design Framework

Unlike other design processes, the novelty of this framework is that it proposes a comprehensive method that can be used to design progressive collapse resistant structures while ensuring optimum efficiency and minimal carbon expenditure. This is since its based on an iterative process that assesses members individually rather than following a set of overly conservative or insufficient assumptions.

3.0 Connection Design

One of the major assumptions associated with the proposed framework is that non-linear deformation will only occur at the locations of plastic hinges which are expected to form within members rather than at joint locations. This helps eliminate the risk of developing a mechanism and consequently collapse. This is typically achieved by adopting plated connections in which the joints are significantly stronger and stiffer than the attached members. This type of connection is mostly used in transfer structures of this large scale as it possesses high strength and stiffness achieved by adding more plates as required. The detrimental drawback of this conventional method which drove the design team to seek alternative more advanced options is the immense amount of additional material, welding and embodied carbon associated with it. Furthermore, since the truss is exposed and acts as an architectural statement, an aesthetically finer solution was required.

In collaboration with the project’s steel fabrication team, BHC Ltd., reduced beam section (RBS) connections were developed and adopted (Figure 3.1). The innovative concept behind RBS connections is to remove materials in specific locations of the beams creating grooved sections that are weaker than joints to ensure the formation of the plastic hinges at the required locations. The superiority of RBS connections is that the required design behaviour can be achieved by removing material, which can then be recycled or reused, rather than adding a significant amount of steel as plating. This leads to remarkable reductions in the material, cost, required fabrication and embodied carbon of the building. Approximately 5% reduction in the truss weight was achieved with RBS connections resulting in carbon saving of 370 tCo2.

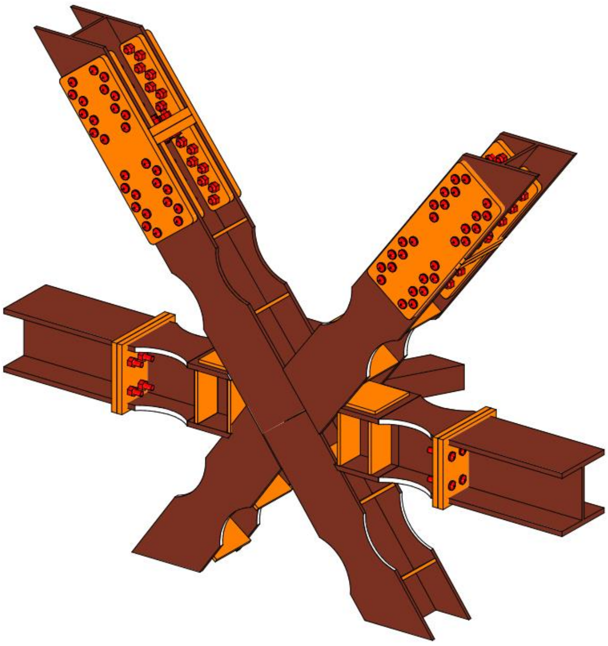

Figure 3.1-Adopted RBS connections

The design process of RBS connections has not yet been codified in the Eurocodes. Thus, the design of these connections was dependent on knowledge gathered from previous case studies, codes such as GSA 2016, and research, including that conducted by Engelhardt (1999) and Dinu et al. (2017). Although a reasonable amount of guidance was acquired from the various sources, experimental testing for this type of connection under the encountered scale of forces, ranging up to almost 30 MN of axial force, was yet to be performed. Thus, in further collaboration with BHC Ltd and the University of Sheffield, unprecedented full-scale testing of RBS connections is being planned, subject to the availability of funding. The acquired data from this testing will help simulate the predicted performance of the connections and further prove their suitability for wider applications to ensure their significant benefits are best employed.

4.0 Additional Considerations

Throughout the course of this design process, the main aims of the design team were to ensure optimisation, cost-effectiveness and minimal embodied carbon for the project. To achieve this, further research was conducted around various aspects. To ensure the best optimisation for the truss members, several iterations were undergone for each of the removed columns resulting in producing over 600,000 data points in the analysis process. This data required to be heavily processed to acquire the connection forces and ensure effective communication to the wider project team. Typically, this data could be sorted manually which highly increases the probability of human error and time costs. Thus, initially a macro-spread sheet was developed to help in the process reducing the required time to extract the data from 6 months to 2 months. Although, some improvement was seen, the team wanted to achieve the maximum efficiency possible. Thus, Renaissance's engineers programmed an original code using MATLAB that can identify the members attached to each joint and produce the relevant forces for each of those members under each load case. This resulted in fully automated extraction and analysis of data which required only 5 working days to develop the MATLAB code. This demonstrates how the implementation of technology can reduce the time associated with a task from months to hours, resulting in increased resource efficiency, reduced cost and higher carbon savings.

5.0 Summary and conclusions

To combat the challenges associated with this project, the design team at Renaissance undertook a one-of-a-kind approach to design a transfer truss. This was achieved by:

- Compiling a progressive collapse resistance framework that could be applied to multiple types of high-risk structures.
- Prioritising the efficiency of the structure from an embodied carbon perspective as well as monetary and material savings.
- Development of RBS connections which can result in extensive material savings when applied to different types of transfer structures, both small and large in scale.
- Exemplifying how research and technology could be applied in the industry to provide innovative solutions to help achieve ground-breaking improvements in structural resilience, efficiency and embodied carbon levels.

6.0 Dissemination of Information

Given the lack of a comprehensive framework to design Class 3 Structures to resist disproportionate collapse, the work carried out for the Viadux Project can result in addition to the knowledge by dissemination of information as below:

- An article within the Structural Engineer journal will be published regarding the development of the Progressive Collapse Framework.
- A conference paper of behaviour of Reduced beam section connections in Trusses under accidental column loss scenarios will be aimed to publish at the ICSRSCP 2022: 16. International Conference on Seismic Resistant Structures and Collapse Prevention-October Los Angeles, United States
- Full scale testing results and FE modelling simulation of the RBS connection in the transfer trusses will be published in a journal paper in Engineering Structures.

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