Structural modelling, analysis and design of composite steel frame building using an integrated design approach

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ABSTRACT: With modern computerisation, structural analysis and design practice have changed significantly over the last two decades. Design practice now requires robust design methodologies that can save time, produce cost-effective solutions, reduce human error, and be able to produce fully compatible building information models (BIM). In this context, the paper presents a robust design approach for a composite steel frame building project. In this approach, steel structural elements can be modelled, analysed, design and detailed in a unified computational framework based on the 'MasterSeries' software package, which incorporates design variables, material specification, loading combinations, connection details, default set code standard criterion, computational solver, composite beam design, detailing procedures, bar bending schedule, etc. To demonstrate the applicability, the methodology was applied to a live project in which a 3D model of the two-storey composite steel frame building was developed and designed as per the Eurocode EC3 standard. The output results were compared and validated through theoretical calculations established as part of the design process. The results are presented in terms of the member sizes established, bending moment and shear force diagrams, including connection details of the structural steel elements. In addition, the model developed was found to be fully compatible with the building information modelling process incorporating other engineering disciplines, such as architectural and mechanical/electrical to develop a fully co-ordinated federated model in order to identify and resolve potential cross-discipline design clashes. To resolve design clashes, Naviswork software was used throughout the BIM process. It is concluded that a cost-efficient, fully integrated design can be successfully achieved using the integrated methodology presented herein. Moreover, the work presented can be used as a reference study for future similar structural engineering building-design projects.

KEY WORDS: Steel building, composite beams, Eurocode, building information modelling

1 INTRODUCTION

Building design-projects typically require a tedious amount of work from its inception. This work includes setting up design loads, sizing structural members, producing analytical model, designing multi-scale (component to individual) members, and establishing detailing of the structural members to its core. To establish this work, structural engineers typically use various commercial software packages (based on the level of confidence and user friendly interface) frequently performing analysis using one software (Etabs, STAAD, Robot etc.) and structural-design part using another (SAFE, Tedds etc.) or through manual calculations, incorporating steel connection design and detailing aspect through other analytical means. This form of working methodology is called conventional design approach.

With advanced computerisation, another form of working methodology is emerging known as Integrated design approach. In this approach, structural modelling, analysis, design and detailing can be established in a unified computational framework. This framework can be achieved through Masterseries software package [1]. This software package allows the modelling of almost all type of structural members and provides design and detailing of the structural members under a one window operation. However, it is important to assess the potential capability and benefits of the relatively integrated design approach for structural engineering applications. Moreover, there is a dearth of research in the literature that covers the application of integrated design approach for composite steel frame building designed using the Eurocode.

With the ever growing demand of construction activities in Ireland, engineers are now looking for a 3D virtual representation of the design model where they can resolve complex design issues in the early stages of planning, increase robustness of the design team activities, and maintain a healthy coordination among different engineering disciplines in order to produce a cost-effective engineered solution. In this context, building information modelling (BIM) process offers a digital platform for generating a virtual image of the theoretical model. It is currently the most common coordinated framework for a new way of approaching the design, construction, and maintenance of buildings. In this study, the BIM application is limited to the development of building design process. By definition, the BIM process is a set of interacting policies, processes, and technologies generating a methodology to manage the essential building design and project data in digital format through the buildings's lifeycle [2]. However, there is a lack of coherent understanding on the implementation of the BIM process, particularly from the structural engineering point of view. A possible reason is the lack of awareness and absence of advanced engineering skills together with equivocal implementation of BIM in the design practice.

In this context, this paper presents a unified design approach incorporating BIM for application to modelling of composite steel frame building design. With this approach, a steel frame building can be analysed and design in a unified computational framework and can be employed to develop federated engineering model based on the BIM application. The application of the unified methodology can lead to a significant saving in terms of design set-up and model run-time, and, importantly incorporates any significant changes that may arise during construction, which is an improvement of the previous design practice. A study of the structural members was carried out in terms of bending moment, shear force, and axial compression-tension force, and typical sizes of the structural members that was established for this building design-project are presented.

2 DEVELOPMENT OF BUILDING STRUCTURAL LAYOUT

The purpose of this sample building is to provide water sample testing services for both public and private sectors in Ireland. The building comprises G+1 storey of composite steel frame. In particular, the superstructure of the building is comprised of steel frame construction, and the sub-structure is comprised of reinforced concrete. Steel frames are typically flexible to accommodate mechanical and electrical services, structural renovation and are considered as light weight structure compared to traditional reinforced concrete structures. This forms the basis of employing composite steel frame design in this industrial orientated-project.

Composite steel frame design can have various construction forms, for example, slim floor construction and/or standard composite slab to beam design construction. In this project, composite beam construction was used where a profiled metal deck (this can be trapezoidal or parabolic shape) is supported by steel beams through shear stud connections. These shear studs are typically welded to the top flange of steel beams and embedded into in-situ concrete slab to establish a composite bond between steel beams and concrete slab. This form of composite bond creates a load distribution path for the suspended slab, resists uplift forces resulting due to slab bending and improves the diaphragm action of slab against wind loading. A minimum amount of steel reinforcement is used in the composite slab to control thermal and shrinkage cracks. An unpropped metal deck construction was used in the composite slab design – meaning that separate temporary back propping of deck is not required during slab concreting, leading to a reduced temporary work requirement and faster construction programme.

Composite beam design can be achieved by two methods, (i) BS 5950-3.1:2000 [3], and (ii) BS EN 1994-1-1:2004 [4]. Both standards evaluated the bending resistance of the composite beam using plasticity theory in which the cross-section should not be subjected to the effect of local buckling. Such sections can be classified as Class 1 cross-section as per Eurocode 3 [5]. Although, both standards are acceptable from design point of view, however, they are slightly different in terms of stress evaluation procedure, material factors, effective width evaluation etc. In this study, BS 5950-3.1:2000 [3] standard was used due to the fact that it has simplified calculations and it has been used in previous projects with confidence. In addition, the composite beam design was only applied to first floor slab construction, the roof was designed as light-weight metal deck as it will be only used for limited access, such as maintenance. The deck type and the corresponding loading is shown in the colour coded form as depicted in Figure 1.

The main structural system is comprised of steel portal frames and braced steel framing elements. The portal frame only occurs first floor to upper roof. The main frame up to first floor level is a simple stick built braced frame. A possible reason of employing mix-mode framing system is to suit architectural and mechanical/electrical layout. Portal frames exclude the need of employing vertical bracing and resist horizontal loads through moment connections. Braced steel frames resist lateral loads by bracing elements through truss action, and the connections between beam and columns are typically only designed for shear forces. The steel columns are connected by short concrete stub columns with pad/isolated foundations. The concrete stubs were designed to carry the vertical axial load coming directly from the steel columns as well as for base shear force caused by vertical bracing as a result of lateral loads, such as wind loading. The stub sizes (ST1 and ST2) are shown in the Figure 1. Tie beams are also used to increase the lateral stability of the stubs columns against lateral loads. . The location and size of tie beam (CB1) is shown in the Figure 1. Other structural steel elements (beams, columns, and bracing members) that were employed in this project are shown in the Figure 1.

Foundation design can be a complex task when dealing with soil conditions on site of low bearing capacity. The bearing stratum (medium-stiff clay) was found 2m below existing ground level. However, it was noticed that setting up formation level below 2m would excessively increase the height of the stub columns and may end up with constructability issues (temporary groundwater control etc) on site. In order to achieve a formation level above the ground water, a rock fill was proposed between the stiff clay layer and the underside of the pad foundation. Another advantage for building up fill material under foundation and adding new soil above foundation is the local improvement of soil pockets located right under the ground slab. The ground floor slab was intended to be designed as fully supported ground bearing slab. However, it was noticed that to replace a bulk of 2m weak soil for the entire building foot print is uneconomical. Therefore, the ground floor slab is designed as one-way ground bearing hybrid slab meaning that part of this slab spanning between two foundation footprints act as suspended slab, which can be analytically modelled as beam with two fixed ends condition. The resulting sagging moment at the mid-span of beam can be used to design the main rebar of the suspended slab in the direction of the spanning, and that resulting hogging moment at supports can be used to design the rebar of part of the slab that sits directly above foundation.

3 DESIGN METHODOLOGY

The building design project outlined in section 2 was modelled, analysed, designed, and detailed as per the design methodology presented in the Figure 2. Starting with the basic material properties, density of normal weight of concrete and structural steel material was defined as part of the structural modelling. Geometric modelling is carried out on the basis of the sizes of the structural members set out in accordance with the design loads. Design loads consist of dead load (self-weight of structural members), superimposed dead loads (screed and other finishes), Imposed loads (maximum 7.5kN/m^2 for first floor level), and wind load, which was evaluated based on the

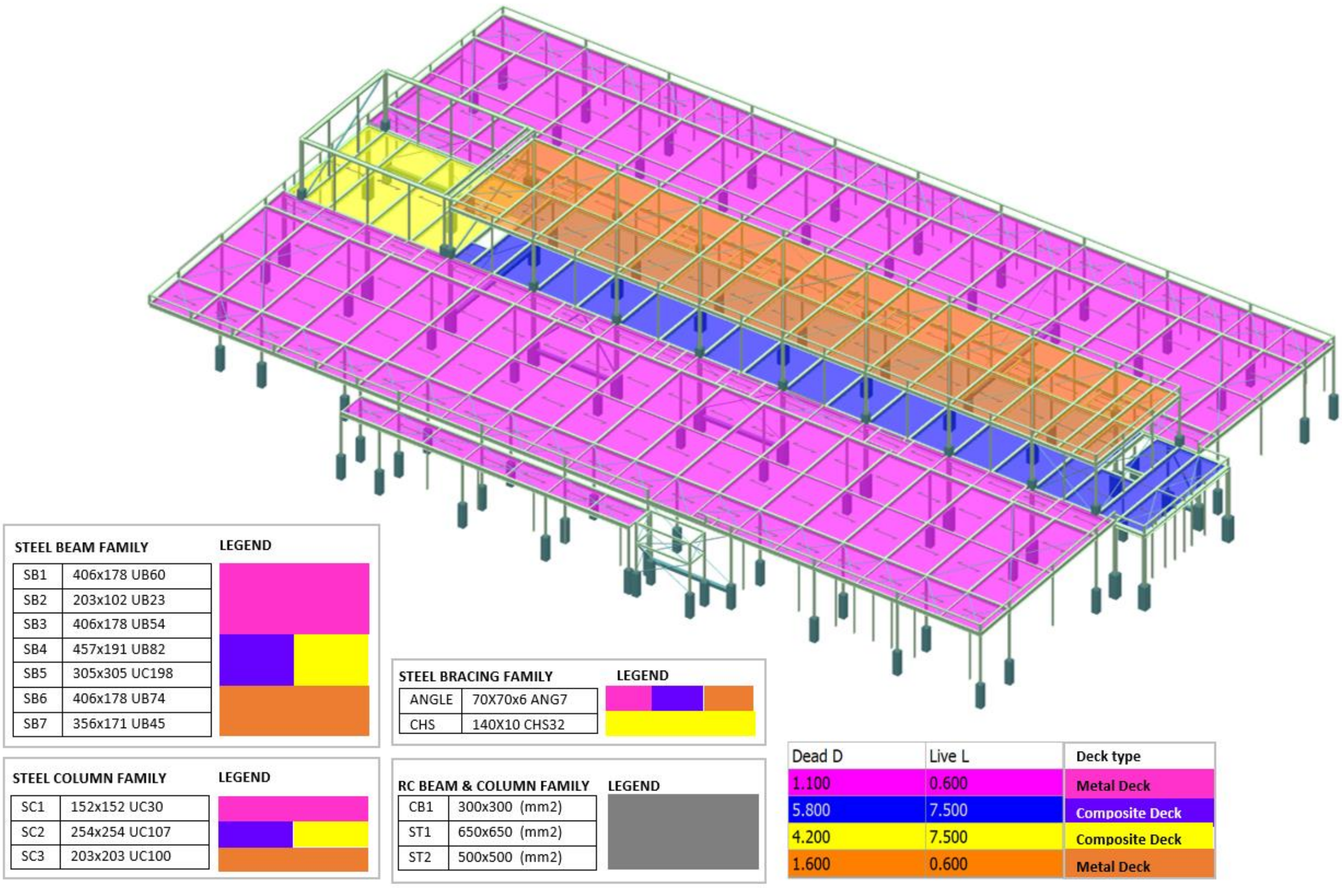

Figure 1. Building layout showing structural framing system – steel beam family, steel column family, steel bracing family, RC beam and column family used in this project. Type of decking systems and the loads (dead + imposed) correspondence to them are also illustrated.

site location and topography characteristic as per the EC1 [6] standard within the building design model. Ireland typically has low seismic activity therefore, no seismic load was defined as part of the design loads. Appropriate end releases were defined to realistically reflect the boundary conditions formed by beam to beam, and beam to column end connections. Pin ended connections were assumed to suit the design of pad/isolated and combined foundation.

Lateral deflection check ensures that the resulting horizontal deflection in columns due to lateral loads are within the permissible limit state for a safe design. However, no specific deflection limits are defined in EC3 [5], instead it is suggested that the deflection criteria for columns should be specified and agreed with the client for each project. On the other hand, BS5950-1:2000 [7] suggests that horizontal deflection in each storey of a building with more than one storey for a braced steel frame structure should be limited to the criterion given by Equation 1;

$$H/300 \text{ (Braced steel frames)} \quad (1)$$

$$H/200 \text{ (Steel portal frames)} \quad (2)$$

where H is the storey height.

For steel portal frames, it is suggested that the requirement to limit the horizontal deflection is governed by the cladding system. Careful specification and detailing of cladding is necessary to ensure that the flexible behaviour of a steel portal frame is not detrimental to the performance of the envelope. In addition, the light weight cladding ($<0.12kN/m^2$) is another contributing factor in setting up the deflection limit for steel portal frames. Therefore, the criterion, defined in Equation 2 was deemed appropriate to limit the horizontal deflection in the portal frames for this project. Equation 1 is used as a limiting criterion for braced steel frames.

Analysis of the structural members was carried out against various load combinations (dead, imposed, wind), including notional horizontal load combination to cover the effect of framing imperfection resulting during construction. Briefly, imperfection can be any irregularity that deviates from the idealised geometry and that it can be categorised as global and local imperfection. By definition, global imperfection (geometric and residual stresses) are those that persist along the length of the member after fabrication, and those along the section as local imperfection. Details on the finite element (FE) modelling of imperfection for braced steel frame members and components is covered by NUIG structures research group [8-11].

The analytical model was then used to design the structural steel members based on the EC3 [5] standard, and the reinforced concrete members using EC2 [12], incorporating composite beam design as per BS5950 [3], detailed connection design as per EC3 [5], and detailing structural concrete as per EC2 [12] standard. The aforementioned structural model was

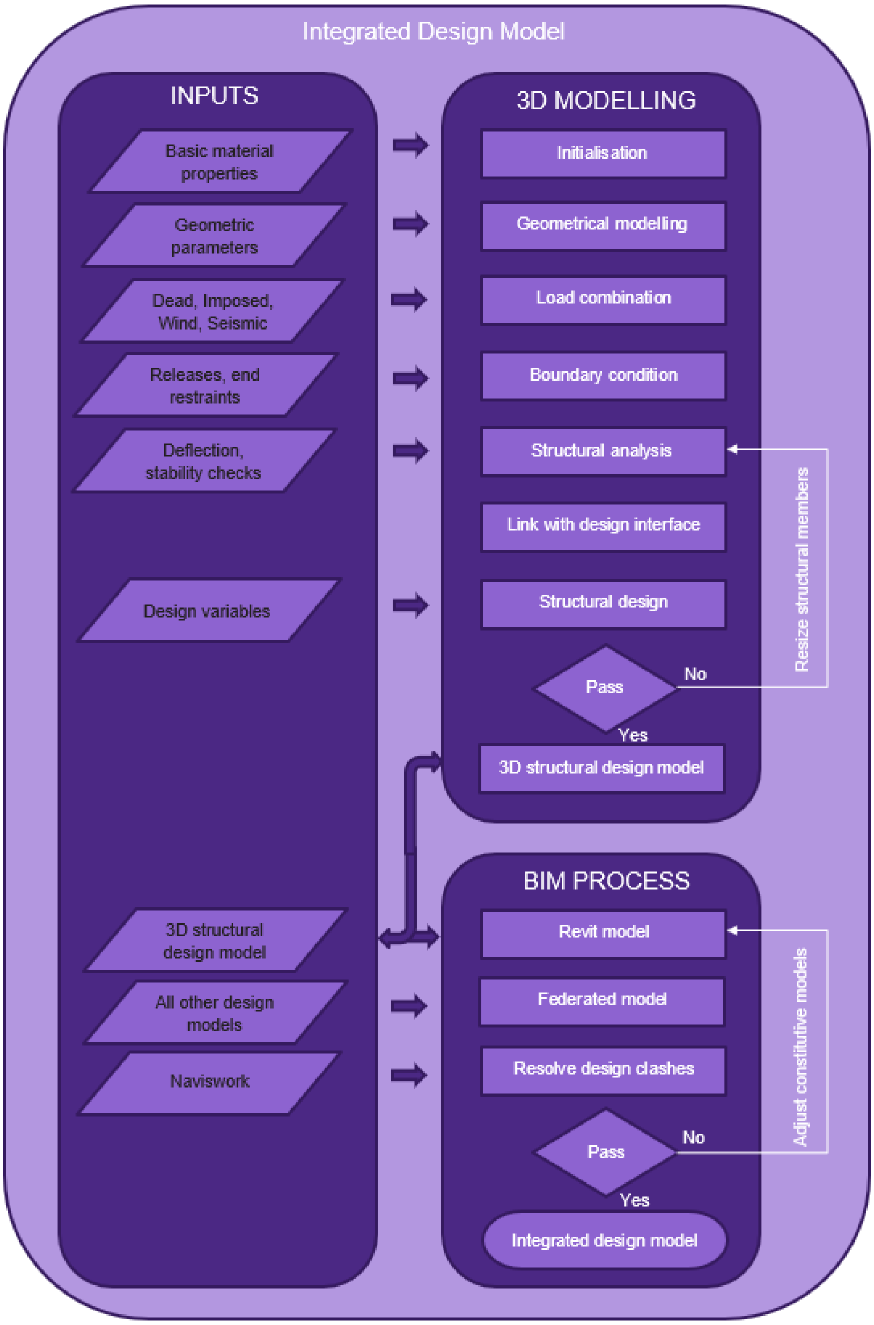

Figure 2. Schematic illustration of unified design methodology representing input data and data processing units as part of the design framework..

implemented using commerical software package Masterseries v.2019 [1].

The design model was then brought into the building information modelling process with the help of interaction tool built-in within the computational framework. This interaction tool allows 'to and from' synchronization of models, and transform design variables into BIM interface where the structural members possess identical properties (material and geometric) they have had in the structural model. Other structural details (metal deck, trimming steel etc.) and non-structural elements (cladding, screed etc) that are important from constructability point of view are then modelled in order to develop realistic civil and structural (C&S) building design model. Independent BIM based models from other engineering disciplines (architecture, mechanical, and electrical) were incorporated with the C&S model to establish a federated model. This model was then used to investigate the clashes resulting due to merging of engineering models, with the aid of Naviswork [13] – a package of BIM process. A detailed output report was requested to quantify the number of clashes, and the location of confrontation w.r.t the cartesian coordinate system. Examples of design clashes are shown in the Figure 3. These clashes were then locally resolved by adjusting structural/non-structural elements without compromising their intended design. The application of the federated model has led to the development of a predictive model that is able to predict future clashes at any stage of the building life-cycle considering existing as-built models in place.

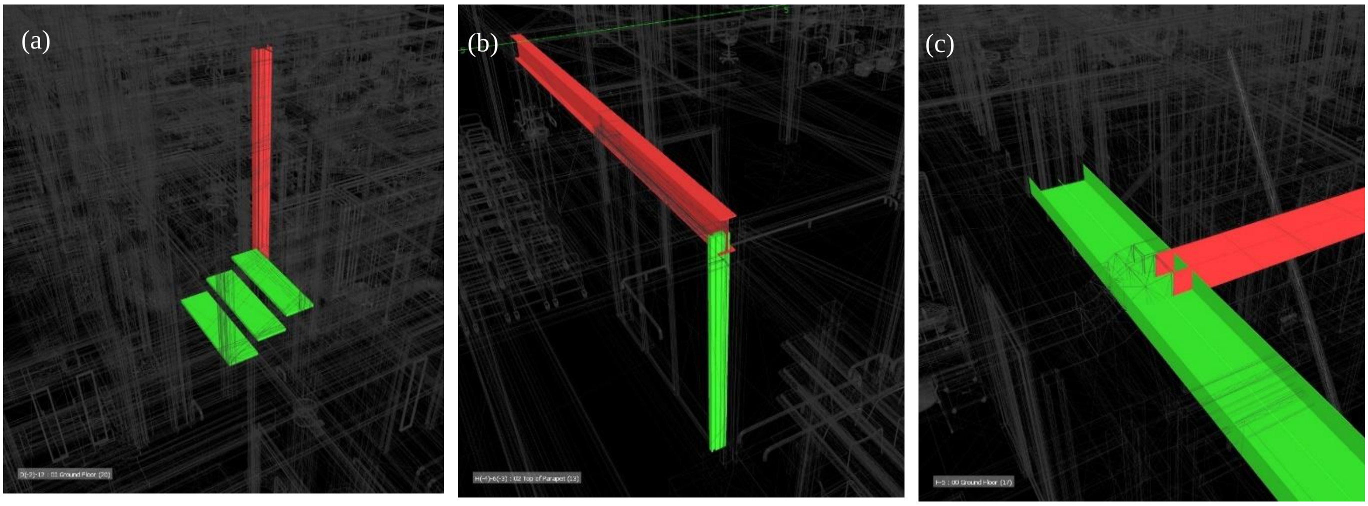

Figure 3. Naviswork output showing design clashes resulting due to merging of civil engineering building design models: (a) clash between architectural stairs and structural steel PFC column, (b) confrontation issue between main steel beam and trimming steel around the door, and (c) cable tray clash against mechanical ducting.

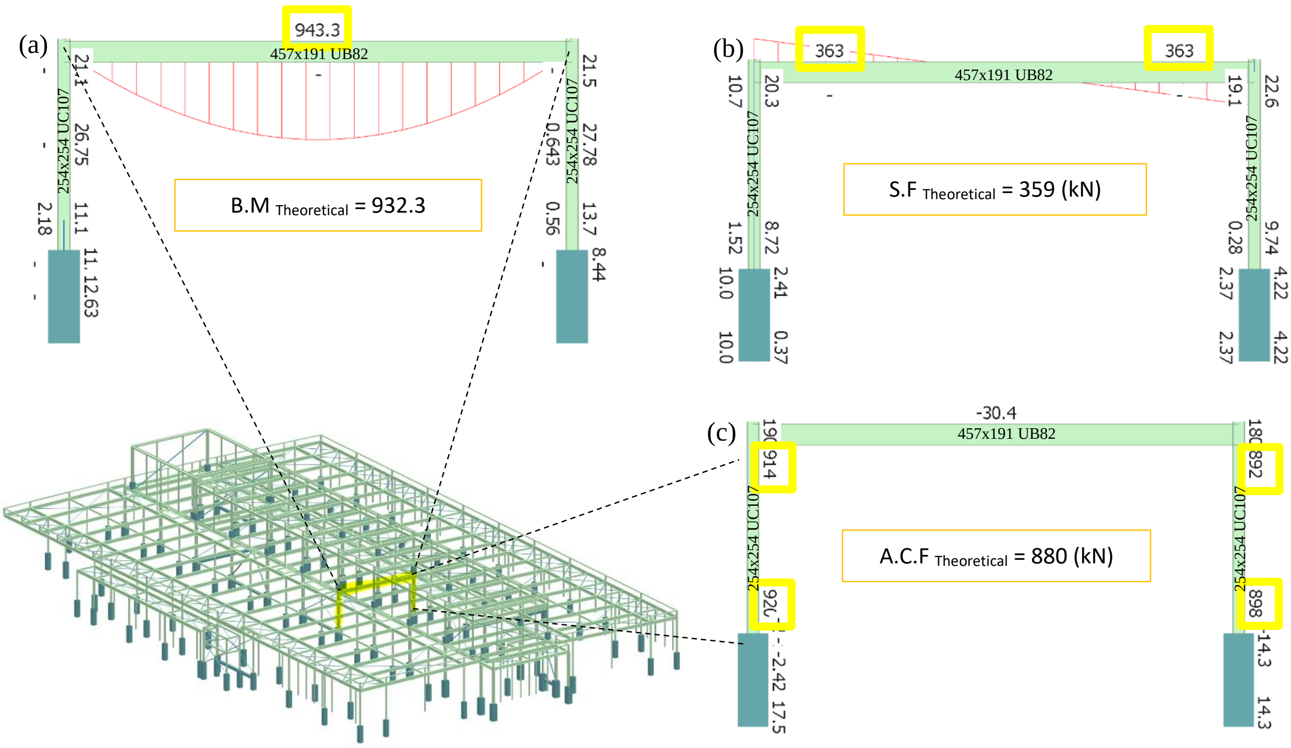

Figure 4. Result outputs obtained from 3D numerical model: (a) maximum bending moment, (b) maximum shear force, and (c) maximum axial compression force.

4 DISCUSSION AND RESULTS

The structural model developed in Section 3 was used to generate analytical results in terms of bending moment (B.M), shear force (S.F), and axial compression force (A.C.F). Starting with bending moment magnitude, the results obtained from analysis and theoretical calculations are found in good agreement for composite beam design with convergence ratio (theoretical/numerical) of 0.99. As expected, the maximum bending moment occurs for the internal beams where 7.5kN/m^2 of imposed load was applied, as shown in the Figure 4(a). The theoretical B.M was calculated based on the area supported by beam under consideration.

Similarly, a good agreement is found between analytical and theoretical calculations for the shear force magnitude developed in the steel beams due to design loads. A comparison of shear force magnitude for the aforementioned steel beam is shown in the Figure 4(b), with the convergence ratio of 0.99. While comparing results of axial force in columns, it is found that theoretical results are 0.96 times the hand calculation results, which is acceptable (Figure 4(c)). As a general approach rule, the utilisation ratio (capacity/demand) of all structural elements were kept under 80%. The remaining 20% is left to account for the future renovation. In addition, typical

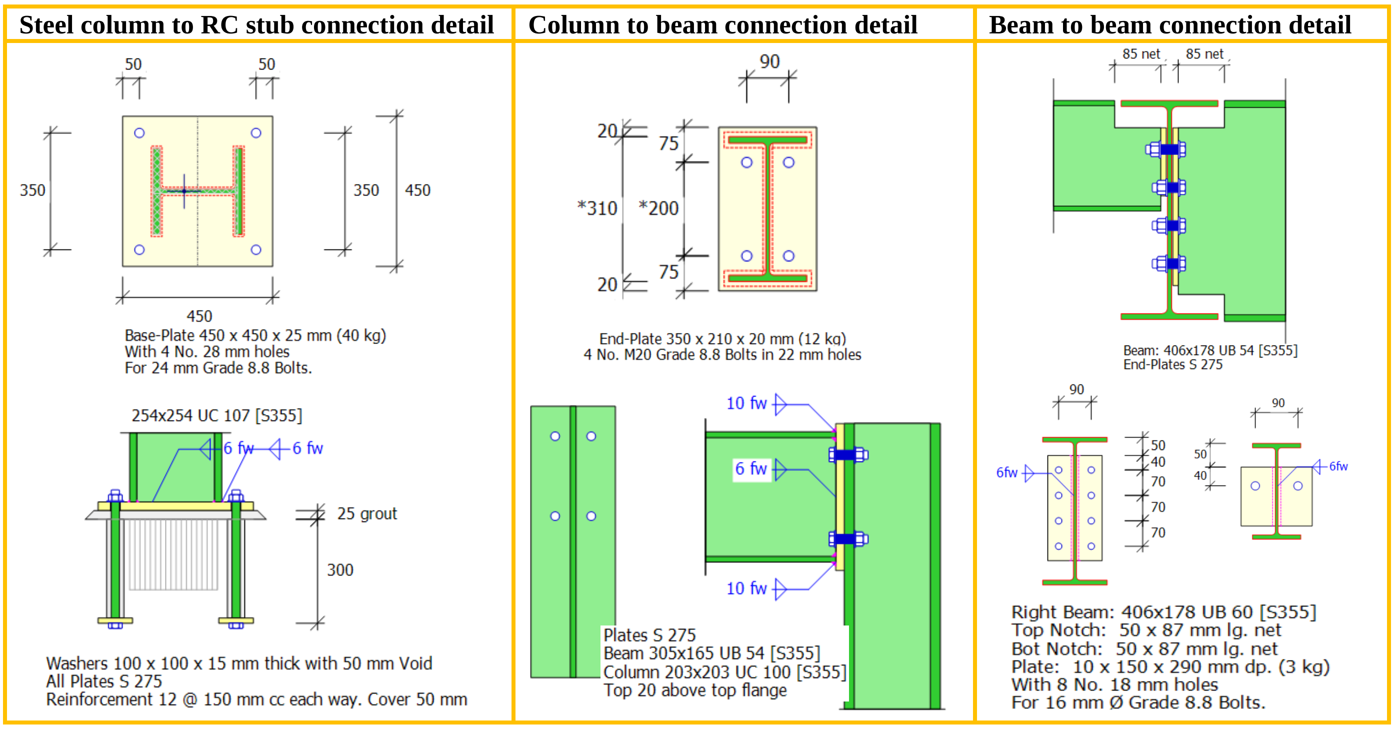

Figure 5. Connection design output obtained from numerical model (typical details).

connection details obtained from numerical model for base plate design, column to beam connection design, and beam to beam connection design are shown in the Figure 5.

While assessing the lateral behaviour of the building frame, it was found that steel portal frame exhibits greater in-plane lateral deflection compared to braced steel frames for the similar loading protocol. This is due to the fact that portal frame resist lateral sway through moment connections, while braced steel frames resist lateral deflection through diagonal steel braces, which provide greater stiffness and strength to the system. The resulting lateral deflection was found less than the allowable permissible deflection limit state defined in the Section 3.

5 CONCLUSION

In this paper, it is shown that a unified design methodology offers a comprehensive design approach when dealing with multi-disciplinary building design project, such as design of industrial laboratory building. It combines the blend of different engineering disciplines under a platform to coordinate and interact principal design features that are mutually important for a complex, safe design. Moreover, it offers a road map to set design tasks that are required for a successful and well-organised project. With this methodology, the design information can be retained in a digital format, which is easy to handle, and convenient to implement for future BIM processes, such as time unit (4D) and cost data (5D).

The future work will involve integration of structural health monitoring system into the design methodology presented herein, to gather and allow the digital data to process itself through cyber physical system. Thus, achieving the purpose of next generation models known as industry 4.0.

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