Automated Clash Resolution of Steel Rebar in RC Beam – Column Joints using BIM and GA

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Abstract –

Design of steel rebar in reinforced concrete (RC) members is usually conducted individually based on loading conditions, support conditions, and geometric conditions of the considered RC members only. Member-member interactions are rarely considered at the design stage, leading to potential rebar clashes (hard clash) or congestion (soft clash) at beam-column joints on construction sites. Currently, rebar clashes and congestion are often manually identified and resolved at the construction stage by site engineers or workers, which is a tedious and time consuming process. The building information modeling (BIM) technology allows us to digitally represent the detailing of steel rebar and transfer the detailing information to structural analysis software. However, automated identification and resolution of steel rebar clashes and congestion in RC members are lacking in the existing BIM software packages.

This paper presents an automated steel rebar design framework based on BIM and genetic algorithm (GA) that considers and avoids rebar clashes and congestion at RC beam-column joints. Each beam-column interaction in a given RC frame is first analyzed to find out the type of each beam-column joint, such as T Joint and + Joint. GA is used to generate a first stage population containing steel rebar number and location for each RC member. Each individual of the population is then checked at all beam-column joints to avoid hard clashes between inter-member steel rebar. Optimal rebar diameter combination (with minimum rebar area) for each clash-free individual of the population is then calculated using the second stage GA based steel rebar optimization engine. The optimization engine contains a built-in checking function to avoid congestion between steel rebar. An illustrative example will be shown to test the developed framework.

Keywords –

Clash Resolution; Beam-Column Joint; Building Information Modelling; Steel Rebar Design; RC Frame

1 Introduction

Steel rebar design is a mandatory step in reinforced concrete (RC) design process. Provided steel rebars should be able to withstand the loads imposed during the life span of RC structures. Besides, steel rebar design should be easy to construct, safe and cost-effective. Currently, steel rebar design for RC members is usually conducted individually based on loading conditions, support conditions, and geometric conditions of the considered RC members only. This leads to potential steel rebar clashes (hard clash) or congestion (soft clash) at beam-column joints. Identification and resolution process of these steel rebar clashes is carried out manually by site engineers or workers at the construction stage. The identification and resolution process is tedious, time consuming and sometimes expensive.

Various studies have been conducted in the past to tackle the problem of clash identification and resolution. Park [1] developed a methodology to generate steel rebar placement sequence to increase productivity. Clashes between various steel rebars were also automatically detected through a developed application programming interface (API). However, only a manual approach was considered for clash resolution. Navon et al. [2] developed a system to identify various constructability problems including rebar congestion and rebar collision. However, rebar clash resolution was still conducted manually by engineers. Radke et al. [3] automated the identification and resolution of spatial clashes for mechanical, electrical and plumbing (MEP) systems. Clashes were identified by determining the distance between centerlines of two objects. The identified clashes were then resolved by moving one of the two entities. However, design constraints were not verified after moving one object. Besides, it was able to solve only limited type of clashes. Wang and Leite [4] carried out a profound study of clashes in MEP systems. A thought process based schema was also developed to store clash based information. The clash based information included description, context, evaluation and management details. However, the developed schema only provided a documentation method to store clash based information without any clash resolution strategy for identified clashes. Moreover, most of the above studies lack full automation in providing required input to the clash detection and resolution problem. Therefore, developing an automated BIM-based framework to provide clash resolution strategy will be of utter importance in architecture, engineering and construction (AEC) industry.

Therefore, the objective of present paper is to develop a BIM-based automated clash free steel rebar design optimization framework according to regional design codes. The previously developed Hybrid GA-based steel rebar optimization engine [5] will be integrated with the developed BIM-based automated clash free steel rebar design framework to provide optimum steel rebar diameters for different RC elements. Since RC frames consist of mainly RC beams and RC columns, RC frames having RC beams and RC columns are considered to analyze the performance of the developed framework.

2 The Proposed BIM-based Automated Clash Free Steel Rebar Design Framework

The proposed BIM-based automated clash free steel rebar design framework is explained in this section. The framework consists of 5 modules (Figure 1), namely (1) BIM Model Extraction, (2) Structural Analysis, (3) Beam-Column Joint analysis, (4) Rebar Number Optimization, and (5) Steel Rebar Calculation and Optimization, as follows.

- *(1) BIM Model Extraction*: Requisite functional (e.g., loading and end support conditions) and physical (e.g., cross-sectional information) characteristics for steel reinforcement calculation is extracted from BIM model for further clash free steel reinforcement optimization calculation.
- *(2) Structural Analysis*: The extracted information is then imported into structural analysis software to calculate design bending moment and shear force. Relevant design code recommended safety factors are also considered in the calculation. The calculated results are saved for further calculation.
- *(3) Beam-Column Joint Analysis*: Beam-column interactions at each level of RC frame is analyzed to extract the joint type, such as T joint and + joint. Joint information is saved for further calculation of rebar number in each RC member.
- *(4) Steel Rebar Number Optimization*: Provided rebar number for each RC member is then calculated on the basis of the outcome of the joint type at each level of RC frame. The calculated rebar number for each RC member is then stored for further calculation of rebar diameters.
- *(5) Steel Rebar Calculation and Optimization*: Provided rebar diameters for each RC member are finally calculated considering the calculated rebar number and other conditions stipulated in the regional design code.

The first two modules are straight forward and require no explanation. The rest three modules are explained in Sections 3-5, respectively.

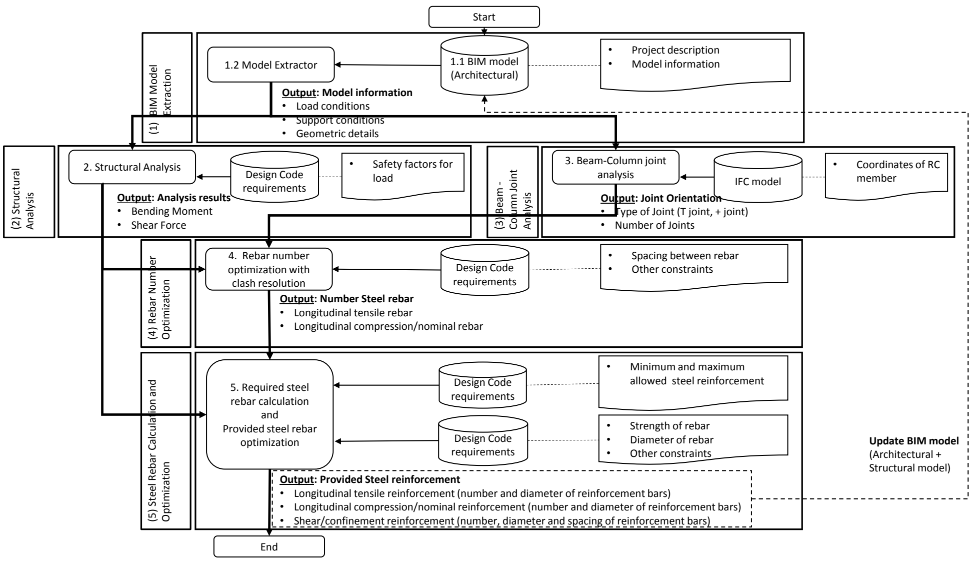

Figure 1. The proposed BIM-based automated clash free steel rebar design framework

3 Beam-Column Joint Analysis

RC frame consists of various types of beam-column joints (e.g., T joint, + joint, etc.) based on orientation and interaction of RC beams and RC columns. Various types of beam-column joints generally encountered in an RC frame are given in Figure 2. Beam-column joint analysis is carried out to classify the type of each beam-column joint in a given RC frame. Classified beam-column joints will further help to calculate the clash free steel rebar number in each RC member (RC beam or RC column) of the considered RC frame. RC frame is first divided into separate levels (floors). Every RC column in each separated level is analysed to extract the connected RC beams with that RC column. A maximum of 4 RC beams can be linked to an RC column at any separated level. Extracted beam-column joint information is stored for further calculation of steel rebar numbers. A total of 10 different types of beam-column joints are considered in the developed BIM-based automated clash free steel rebar design framework.

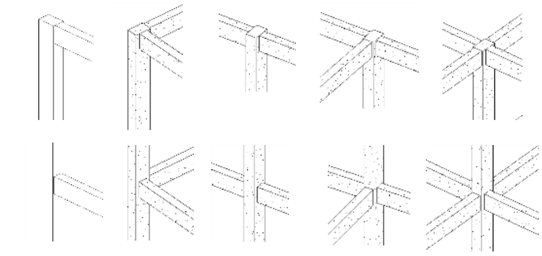

Figure 2. Various types of beam-column joints generally encountered in an RC frame

4 Formulation of Rebar Number Optimization Problem

This section will present the formulation of the objective function for optimization of steel rebar number of each RC element in an RC frame. Section 4.1 presents the steel rebar number range calculation for longitudinal reinforcement as per design code. Section 4.2 describes the compatibility requirements for steel rebars of different RC members. Section 4.3 presents the overall steel rebar number optimization function of a whole RC frame with subjected constraints.

4.1 Steel Rebar Number Range Calculation for Longitudinal Reinforcement

Different regions have different design codes for RC design. For example, both BS8110 and BS4449 are used in Hong Kong and UK. BS8110 deals with the minimum required rebar area depending on building data. The building data include support conditions, loading conditions and geometrical information of all RC members in a given RC frame. BS4449 includes properties of steel rebars such as flexural strength, yield strength and allowable steel rebar diameters. The developed optimization tool considers BS8110 and BS4449, although it can be modified to account for user specific rebar properties (e.g., preferred steel rebar diameter).

The provided longitudinal tensile/compressive/nominal steel reinforcement is the total cross-sectional area (A_s) of longitudinal steel rebar provided at a section, which can be calculated as:

$$A_s = \sum_{i=1}^{t} n_i \pi {d_i}^2 / 4 \tag{1}$$

where d_i is the selected longitudinal rebar diameter from BS4449, n_i is the total number of steel rebar of type i, and t is the number of different diameter types of steel rebar.

The total number of steel rebar (Sn_i) depends on BS8110 as given below:

$$n_{min} <= \left(\sum_1^t n_i \text{ or } Sn_i\right) <= n_{max} \tag{2}$$

where

$$n_{min} = \frac{(b-2*sc)}{Hs_{max}} \tag{3}$$

$$n_{max} = \frac{(b-2*sc)}{Hs_{min}} \tag{4}$$

where b is the width of RC member, sc is the side cover, Hs_{min} is the minimum horizontal steel rebar spacing, and Hs_{max} is the maximum horizontal steel rebar spacing as per the provisions of BS8110 (Figure 3).

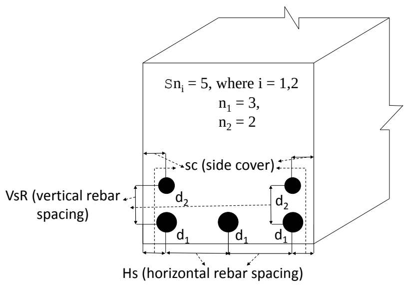

Figure 3. Horizontal and vertical rebar spacing for an RC member

Steel rebar range ($n_{x\ min}$, $n_{x\ max}$ and/or $n_{y\ min}$, $n_{y\ max}$) is calculated for each RC member of RC frame. Steel rebar range is only calculated in x direction ($n_{x\ min}$, $n_{x\ max}$) for RC beam (Figure 4). However, steel rebar range is calculated in both x and y directions ($n_{x\ min}$, $n_{x\ max}$ and $n_{y\ min}$, $n_{y\ max}$) for RC column as orientation of steel rebars in RC column depends on the building data as described before (Figure 5). The calculated steel rebar range for each RC element is stored for further calculation of provided steel rebar number in each RC element.

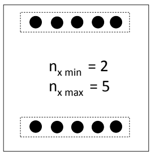

Figure 4. Steel rebar range in x direction for an RC beam

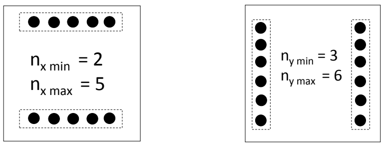

Figure 5. Steel rebar range in x any y directions for an RC column

4.2 Steel Rebar Compatibility

Steel rebar number is then assigned to every RC element of RC frame. Assignment of number of steel rebar depends on the type of beam-column joint and the orientation of rebar in RC column as shown in Figure 6.

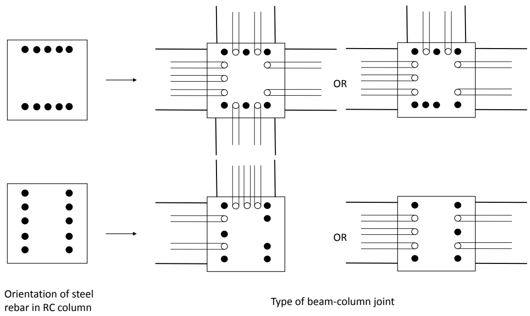

Figure 6. Assignment of steel rebar in RC elements depending on the orientation of RC column reinforcement and type of beam-column joint

It is ensured that the steel rebar number in each beam should not exceed the calculated steel rebar range of beam as given below:

$$n_{x\ min\ i} < n_{b\ i} < n_{x\ max\ i} \quad (5)$$

where, $n_{x\ min\ i}$ and $n_{x\ max\ i}$ are the steel rebar number range for RC beam *i* and $n_{b\ i}$ is the provided number of steel rebar in RC beam *i*.

Moreover, the total number of steel rebars of RC beam and RC column at each beam-column joint should not exceed the rebar number range of that RC column in both directions as given below:

$$n_{x\ min\ i} < n_{b\ j} + n_{c\ i} < n_{x\ max\ i} \quad (6)$$

$$n_{y\ min\ i} < n_{b\ j} + n_{c\ i} < n_{y\ max\ i} \quad (7)$$

where, $n_{x\ min\ i}$ and $n_{x\ max\ i}$ are the steel rebar number range for RC column *i* in x direction. $n_{y\ min\ i}$ and $n_{y\ max\ i}$ are the steel rebar number range for RC column *i* in y direction. $n_{c\ i}$ and $n_{b\ j}$ are the provided numbers of steel rebar in RC column *i* and RC beam *j*, respectively.

Clash number (CNi) is defined as the total number of steel rebar clashes observed at beam-column joint *i* of RC frame. It can be observed that clash between steel rebars of RC beam and RC column will occur when any interaction of RC beam and RC column at each beam-column joint does not satisfy equation 6 or equation 7. A maximum of 4 steel rebar clashes can be observed at any beam-column joint (+ type joint).

4.3 Objective Function for Steel Rebar Number

It can be inferred that the total number of clashes (CN) in an RC frame will be equal to the sum of CNi of every beam-column joint of that RC frame:

$$CN = Obj\_func\ (CNi) = \sum CNi \quad (8)$$

Our objective is to minimize the above objective function in order to have the least amount of clashes in between steel rebars (ideally zero clashes).

5 Steel Reinforcement Calculation and Optimization

The variables considered in RC member design (RC beam or RC column) are similar across all design codes. The considered variables are (1) area of longitudinal tensile reinforcement (A_s), (2) area of longitudinal compression reinforcement (A_s'), and (3) cross-sectional shear area of links at the neutral axis at a section (A_{sv}) which in turn depends on the building data (Section 4.1) and the provisions of BS8110.

A Hybrid GA-based optimization engine for automated optimization of steel reinforcement was developed by Cheng and Mangal [5] to provide the number and different diameter combination of steel rebars. The already developed steel reinforcement optimization engine is modified in this study to provide the different diameter combination of steel rebars for a given steel rebar number for each RC element. The modified engine is integrated with the developed automated clash free steel rebar design framework in order to provide clash free steel rebar design for the whole RC frame.

6 Solving the Steel Reinforcement Optimization using Two Stage Genetic Algorithm

6.1 Introduction to Optimization Algorithm

Optimization of the provided steel rebars depends on both the number of steel rebar and different diameter combination of steel rebars, thus having more than a million possible combinations. Hence, a powerful yet reliable technique is required to arrive at an optimal solution within a reasonable amount of time.

Many heuristic algorithms have been studied and developed to solve above types of NP-Hard problems. Some commonly used heuristics are Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Genetic Algorithms (GA). The two level GA has been developed for this study as described in Section 6.2.

6.2 Optimization Technique for Current Problem

Optimization of provided steel rebars is carried out in two levels. First level includes the calculation of clash free rebar numbers for each RC element of RC frame (Section 4.2) using the developed GA. Second level includes the calculation of different diameter combination for longitudinal tensile/compressive and shear/confinement reinforcement for RC elements for calculated clash free rebar numbers. Different diameter combination calculation is carried out by modifying the already developed hybrid GA-based automated steel reinforcement optimization engine [5].

First level GA for calculation of rebar number is developed to find out the optimum number of steel rebars with minimum clashes (ideally zero clashes i.e., CN = 0). Steel rebar range ($n_{x\ min}$, $n_{x\ max}$ and/or $n_{y\ min}$, $n_{y\ max}$) is calculated for RC elements considering the building data (Section 4.1). Orientation of steel rebars (Figure 5) is then decided for each RC column considering the loading information, end-support information, and geometrical information. Orientation of steel rebars in RC column will help us to decide the available locations for steel rebars for RC beam steel reinforcement. Now, first level GA is developed to assign the steel rebar numbers to each RC element considering the type of beam-column joint (Section 3) and steel rebar orientation in RC columns (Figure 5). The developed first level GA includes the provisions of design code to ensure that the calculated steel rebar number satisfies the design code requirements for practical purpose. Aim of the developed first level GA is to minimize the objective function (Section 4.3), i.e., the total number of steel rebar clashes (CN) in a given RC frame. Compatibility checks (Section 4.2) are carried out to calculate the total number of steel rebar clashes (CN) in a given RC frame. Mutation and Uniform Crossover are also applied to achieve optimal solutions faster. Mutation helps to get out of local optima. It also explores the solution space for better solutions. Uniform crossover is applied to bring more diversity to future generation. Uniform crossover also eliminates the possibility of positional bias. It is not fruitful to repeat the generation process if results within desired thresholds have been achieved or no improvement has been recorded in the subsequent generations (e.g., 100 generations). Therefore, necessary condition is applied to achieve optimal solution in least amount of time. The necessary condition ensures that clash free solution (CN = 0) for a given RC frame has been achieved. The calculated clash free number of steel rebars for each RC element is saved for further calculation of different diameter combination of steel rebars.

Second level optimization includes the calculation of different diameter combination of steel rebars for given clash free number of steel rebars. Already developed hybrid GA-based automated steel reinforcement optimization engine [5] is used for the calculation of different diameter combination of steel rebars. The optimization engine provides minimum steel reinforcement area results for each RC element in a given RC frame. For e.g., optimization engine provide minimum steel rebar area for longitudinal tensile reinforcement, longitudinal compressive reinforcement and shear reinforcement for RC beam as given in Figure 7. The engine also considers the design code requirements and constructability requirements for better applicability of optimized results on construction sites. However, the optimization engine provides both, number and different diameter combination of steel rebars for each RC element (RC beam or RC column) of a given RC frame. Hence, the already developed hybrid GA-based steel reinforcement optimization engine is modified to provide only the optimum different diameter combination (with minimum steel reinforcement area) of steel rebars for given clash free number of steel rebars already calculated in first level GA.

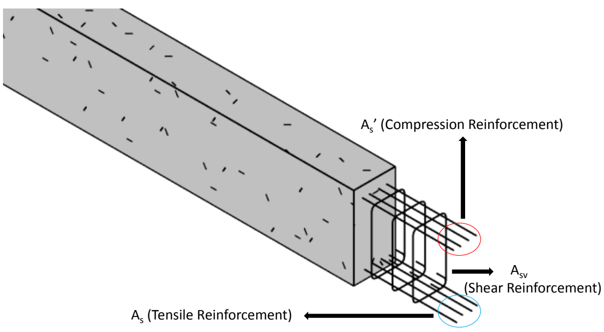

Figure 7. Steel reinforcement optimized by hybrid GA-based steel reinforcement optimization engine for a given RC beam

7 Illustrative Example

A one storey RC frame as a whole is considered in the illustrative example to evaluate the efficiency of the developed BIM-based automated clash free steel rebar design optimization framework at entire frame level. The considered fixed end RC frame is given in Figure 8. Only one type of joint (L joint) is considered in the current illustrative example for evaluation purpose. Uniform dead load (DL) and live load (LL) were applied on the RC beams of the considered RC frame. The developed BIM-based automated clash free steel rebar design optimization framework tool is shown in Figure 9.

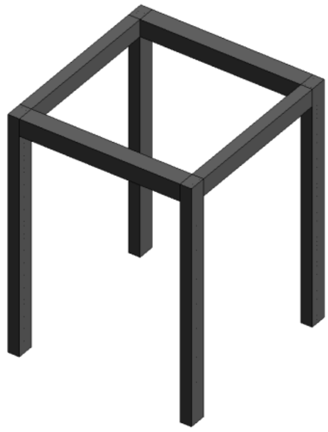

Figure 8. A one-storey fixed end RC frame

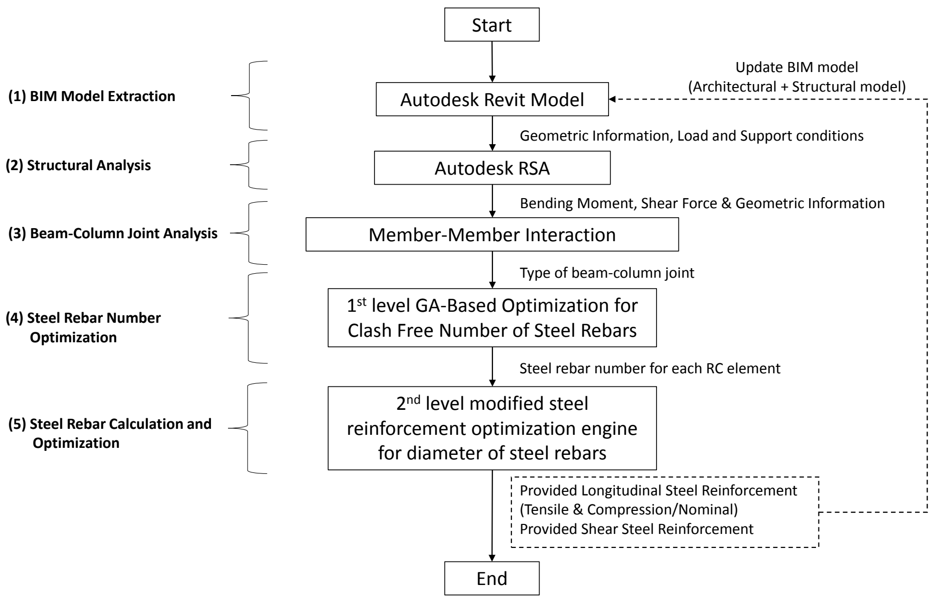

Figure 9. BIM-based automated clash free steel rebar design optimization framework tool

The automated 3D output of the optimized steel rebar is given in Figure 10. One of the single beam-column joint is shown in Figure 11. It can be inferred from Figure 11 that the developed BIM-based automated clash free steel rebar design optimization framework provides optimum results without any steel rebar clashes between steel rebars of different RC element at beam-column joints. 3D output also ensures the extraction of construction drawings as per site requirements. The optimization time varies linearly (O(n)) with the number of RC elements in a given RC frame. For e.g., it takes 40 seconds to optimize the considered RC frame of 4 RC beams and 4 RC columns.

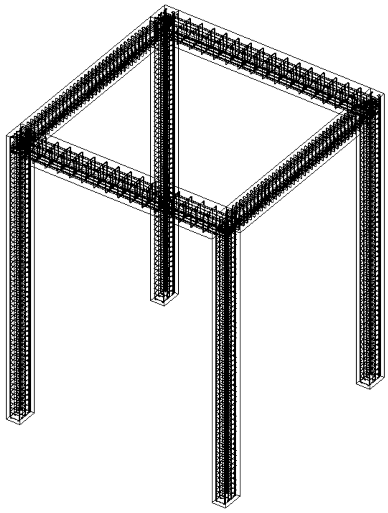

Figure 10. Automated 3D view of the optimized steel rebar for the considered RC frame

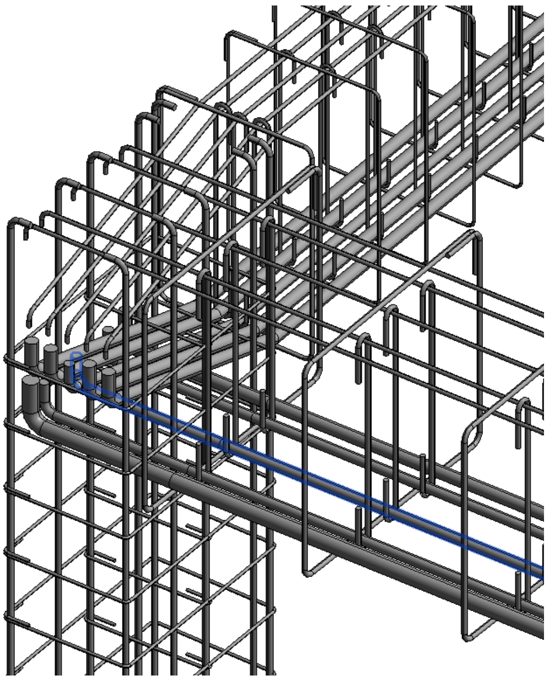

Figure 11. 3D output of one of the beam-column joints of the considered RC frame

8 Conclusion

In this paper, we proposed a BIM-based automated clash free steel rebar design optimization framework for steel reinforcement using two level optimization process. The objective was to provide minimum steel rebar area satisfying the design codes and constructability requirements. Moreover, the provided reinforcement should not have any clashes at beam-column joints. The formulated objective function allows us to consider all the steel rebar clashes at each beam-column joint. Moreover, incorporation of an already developed steel reinforcement optimization engine helped us to find the minimum steel rebar area for given number of steel rebars. The developed BIM-based automated clash free steel rebar design framework provides full automation and interoperability to achieve fast, consistent and site implementable results. An illustrative example demonstrates that the developed framework is effective and efficient. Future work will include the extension of developed framework for the other nine types of beam-column joints.

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