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Design of a high-rise building with hybrid steel-concrete structural elements

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Abstract. This paper presents the challenges encountered during the structural design of a high-rise building located in a seismic area. The construction is an office building, it has 20 stories including the basement levels and a narrow base. Some of the challenges are: providing an accurate structural system to resist the wind and earthquake actions and to design a proper foundation to avoid the overturning of the entire structure. Another important aspect is to limit the stories drift but at the same time provide an open space for the office area. Hybrid structures do not behave like reinforced concrete structures in the sense of Eurocode 2 nor like composite structures in the sense of Eurocode 4. For this reason and due to the lack of knowledge related to the problem of force transmission between steel and concrete the design of structures with hybrid steel-concrete elements can become very difficult. Several models are analysed comparing structural systems made of reinforced concrete, ones made of hybrid steel-concrete elements and several other types of systems.

1. Introduction

The strength and safety of buildings are the most important requirements that must be fulfilled and carefully designed by the structural engineer. This can be achieved by a very clear understanding of the main factors that influence the behaviour of the structure. At the same time, choosing an appropriate structural system is very important.

Since the beginning of time the main aspirations of man were to build upward and to span long distances. The Great Fire in Chicago and the restricted construction area in New York City provided ever so more the need to build upward. Influential engineers and architects teamed up and created the first and second Chicago Schools of architecture. Their work can today be seen in the skyline of these two cities. Fazlur Kahn, a Bangladeshi American structural engineer, recognized that for high-rise buildings the traditional frame system for resisting wind loads is too expensive. He proposed to view the high-rise structure as a huge upright cantilever beam. Thus the framed-tube system was created. This system was later updated to a trussed-tube for John Hancock Centre in Chicago, which has 30% less steel than similar tall buildings, and to a bundled-tube system in Chicago’s Sears Tower (now the Willis Tower) which held the world’s tallest building title for more than 20 years.

These structural systems are efficient for buildings over 50 stories. For 15-20 stories structures the frame system remains the best choice. Rigid frames were developed in the late 1800s for structures made of iron and reinforced concrete. However, if the base of the structure is very narrow compared to its height an inner core needs to be adopted for resisting the lateral loads. Usually, for reinforced concrete structures, the inner core is made of reinforced concrete load bearing walls and the perimeter is made of frames. Even for 10-20 stories buildings very large uplift forces appear at the base of the inner core. These forces can cause the need for very large reinforcement areas for the inner core walls and also foundation design problems. In order to distribute the inner core forces to the perimeter frames deep beams and relatively closely spaced columns on the building perimeter can be adopted. However, often times the architectural solution does not allow for these obstructions. If the buildings height-to-width ratio exceeds 6 the structural system becomes uneconomical [1].

Most modern high-rise buildings incorporate an inner core housing the staircase and elevators along with a column-free floor space between the core and perimeter columns. This system allows for greater functionality, but also effectively disconnects the two major structural elements available to resist the overturning forces. This uncoupling of the inner core from the perimeter frames greatly reduces the system's capacity of resisting lateral loads. One method for solving this problem is to incorporate outriggers. Outriggers have been incorporated in high-rise buildings within the last 35 years. An outrigger is a rigid horizontal structure designed to improve building overturning stiffness and strength by connecting the inner core to the perimeter columns. Depending on the building height range it can be placed at the top of the building, at mid-height or in pairs mid-height and at the top. In order to uniformly distribute the forces to the perimeter columns belts – such as trusses or walls encircling the building – can be implemented at the level where the outrigger is located [1].
Heavily loaded structures can be provided with steel profiles embedded in the concrete. These structures are called hybrid structures or SRC (Steel Reinforced Concrete). These structures are neither reinforced concrete structures in the sense of Eurocode 2 [2], nor composite steel-concrete structures in the sense of Eurocode 4 [3]. There is no guidance in Eurocode 4 on how to evaluate and design this type of structures. There is also no information in classical literature references [4, 5, 6, 7, 8]. Some partial design provisions are mentioned in Eurocode 8 [9] or AISC 341-10 [8], but are not very explicit. In the past decade, extensive experimental research was carried out for the study of hybrid walls [10, 11, 12, 13] and numerical models were developed, such as: multiple vertical-line-element models [14, 15], fibre beam-column models by PEER [16], and multi-layer shear element models [17, 18]. However, all this work did not lead to practical design tools [19].
The aim of this paper is to present different configurations of structural systems – some presented in this chapter – their behaviour and efficiency, for a 17 storey reinforced concrete office building located in a seismic area.

2. Modelling in Etabs

2.1. Etabs software
Etabs is an engineering software package for the structural analysis and design of buildings. The software includes the design of steel and concrete frames with automated optimization, composite beams, composite columns, steel joists and concrete and masonry walls and many other features [20].

2.2. Models description
The common features of the models taken into consideration are the following:

- height range: ground floor and 16 levels;
- ground floor height of 4.5 m and current level height of 3.5 m resulting in a total height of the building of 60.5 m;
- floor dimensions of 19.2 m x 18.0 m;
- open office area having a width of 5.4 m;
- inner core of 8.4 m x 7.2 m with 2 stair cases and 2 elevator shafts;
- inner core thickness of 60 cm for the first three levels, 50 cm for the next three levels and 40 cm for the rest having uniform 80 cm thick bulbs and the corners and at mid-span (see figure 1);
- perimeter frames made of 80 cm x 80 cm columns and 40 cm x 60 cm beams;
- 20 cm thick flat slabs;
- C40/50 concrete grade.

The models taken into consideration have the following particularities:

- model A is the base model having the particularities presented in the previous paragraphs (figure 1);
- model B has 6 HE600B profiles encased in the inner core corners (figure 2) on the first 6 levels effectively creating a hybrid steel-concrete structure. The steel grade is S355;

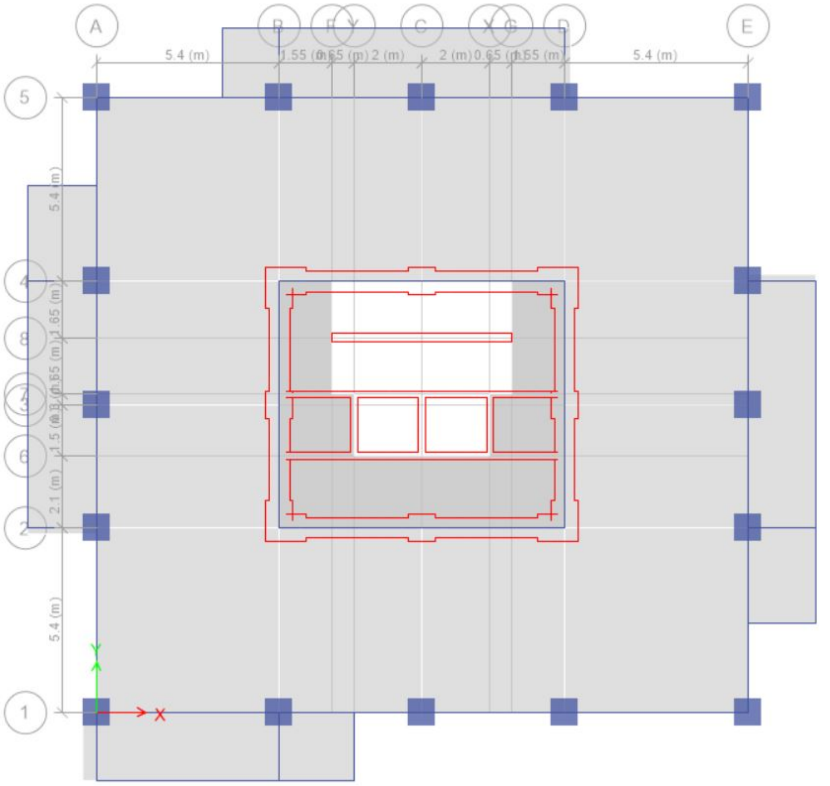

Figure 1. Model A: floor plan.

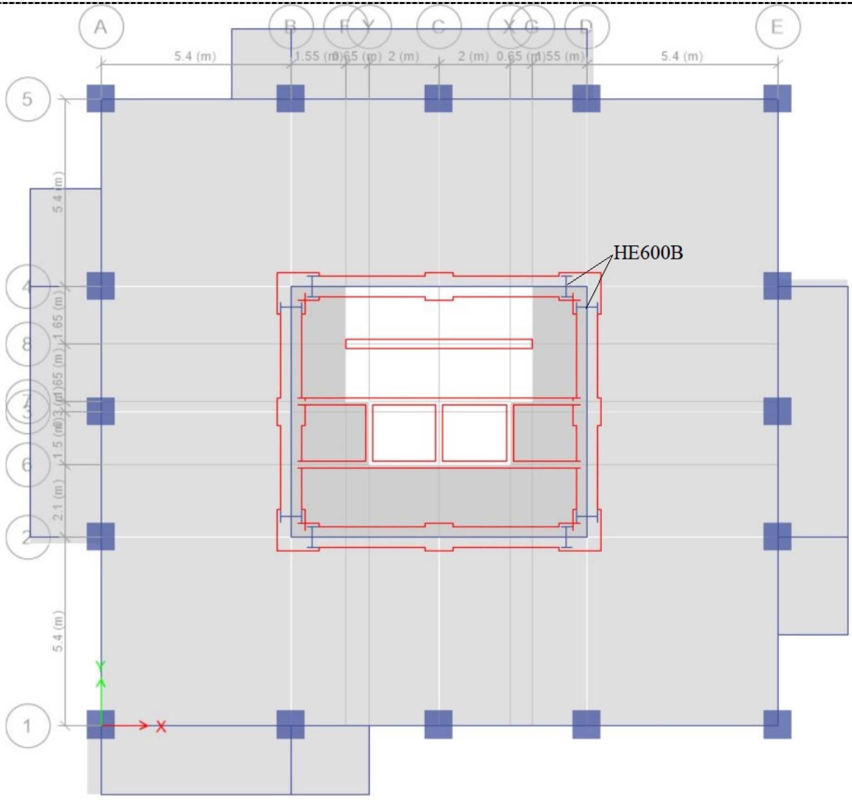

Figure 2. Model B: floor plan.

- model C has one outrigger and a truss belt on the entire perimeter placed at the top level of the building. Reinforced concrete 40 cm x 60 cm beams are used to connect the inner core to the perimeter columns (only at these levels) and 200 mm x 200 mm x 12.5 mm tube profiles are used as braces for the outrigger and belts. The steel grade is S355 (figure 3);
- model D has one outrigger and belts on the height of the 8th floor of the structure. The make-up of the outrigger and belts is the same as model C (figure 4);
- model E has two outriggers and belts: one at the top level and one on the height of the 8th floor of the structure. The make-up of the outrigger and belts is the same as model C (figure 5);
- model F has the inner core connected to the perimeter columns with 40 cm x 60 cm reinforced concrete beams (figure 6).

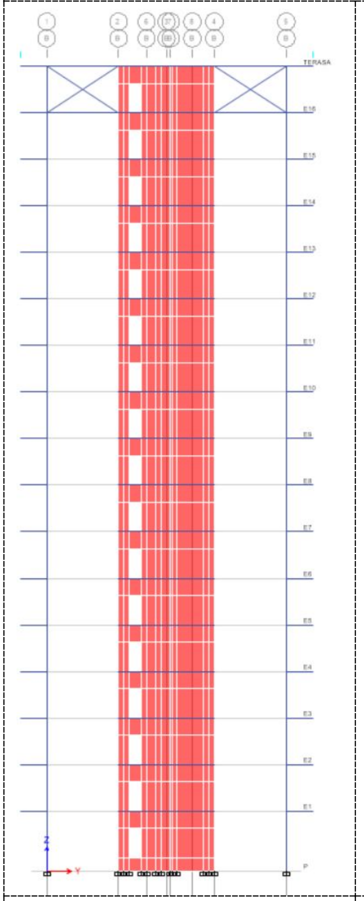

Figure 3. Model C: elevation.

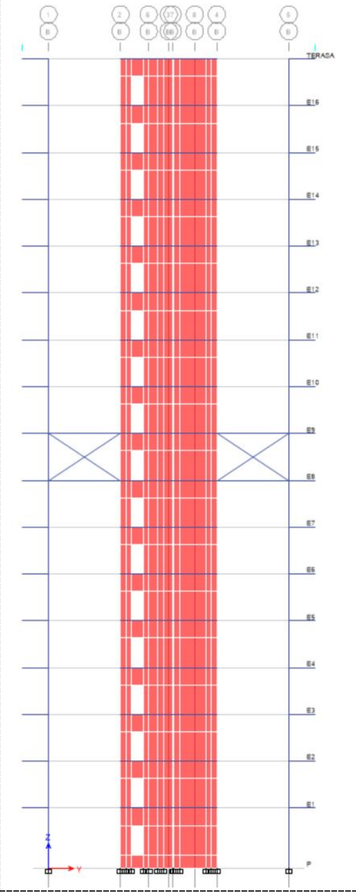

Figure 4. Model D: elevation.

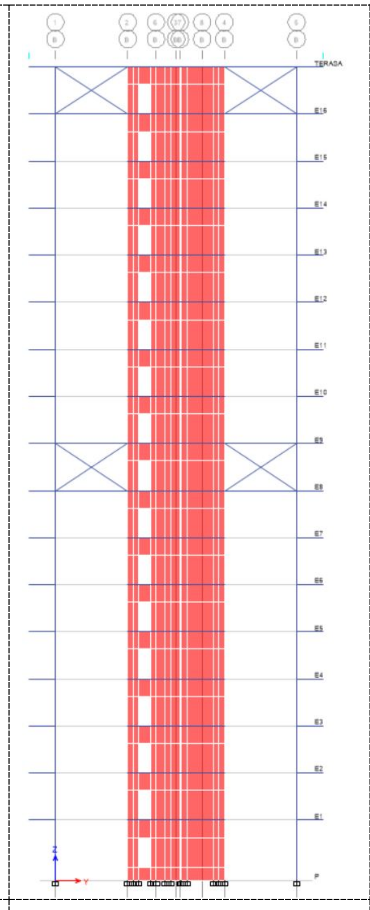

Figure 5. Model E: elevation.

The dimensions of the structural elements were established after a preliminary design according to CR 2-1-1.1/2013 [21] and SR EN 1992-1-1-2004.
The loads are the own weight of the structure estimated by the software, floor finish loads of 2.5 kN/m^2, curtain walls loads of 2.0 kN/m, live loads of 2.5 kN/m^2 in the office area and 3.0 kN/m^2 on the hallways and stairs. The horizontal loads such as wind and earthquake were evaluated according to CR 1-1-4/2012 [22] and P100-1/2013 [23], respectively. The location of the building is Iași, Romania having a peak ground acceleration a_g = 0.25g and a corner period T_C = 0.7 s.

The earthquake action is introduced in the program by using a response spectrum function. The design spectral values are computed according to P100-1/2013 by using equation (1):

$$S_d(T) = a_g \frac{\beta(T)}{q} \tag{1}$$

Where:

- $S_d(T)$ is the design/inelastic spectral value;
- a_g – peak ground acceleration;
- $\beta(T)$ – normalised elastic spectral value;
- q – behaviour factor of the structure.

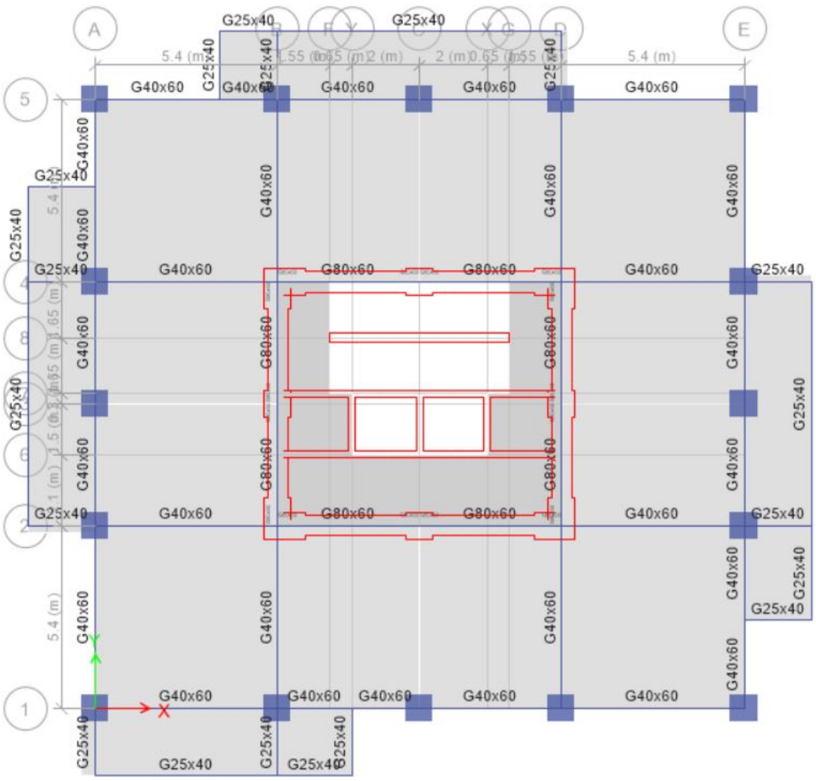

Figure 6. Model F: floor plan.

3. Results

The following results were considered for discussion:

- the required reinforcement area in the inner core of the structure;
- the story drift.

The story drifts for all models is presented in figure 7. According to P100-1/2013, annex E, the allowable storey drift in the Serviceability Limit State is 0.005 and for the Ultimate Limit State is 0.025.

The required reinforcement area for the inner core is designed using the Etabs software. The values at the base of the structure are presented in figure 8. By comparing models A and B, a reduction of reinforcement area of 11.9% was recorded. The models having outriggers and belts (models C, D and E) all present great reductions in reinforcement area (13.3%, 20.8% and 24.2%, respectively). Model F, having reinforced concrete beams linking the inner core to the perimeter columns presents a

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reduction in reinforcement of 15.7% in the inner core, but reinforcement needs to be added for the additional beams.

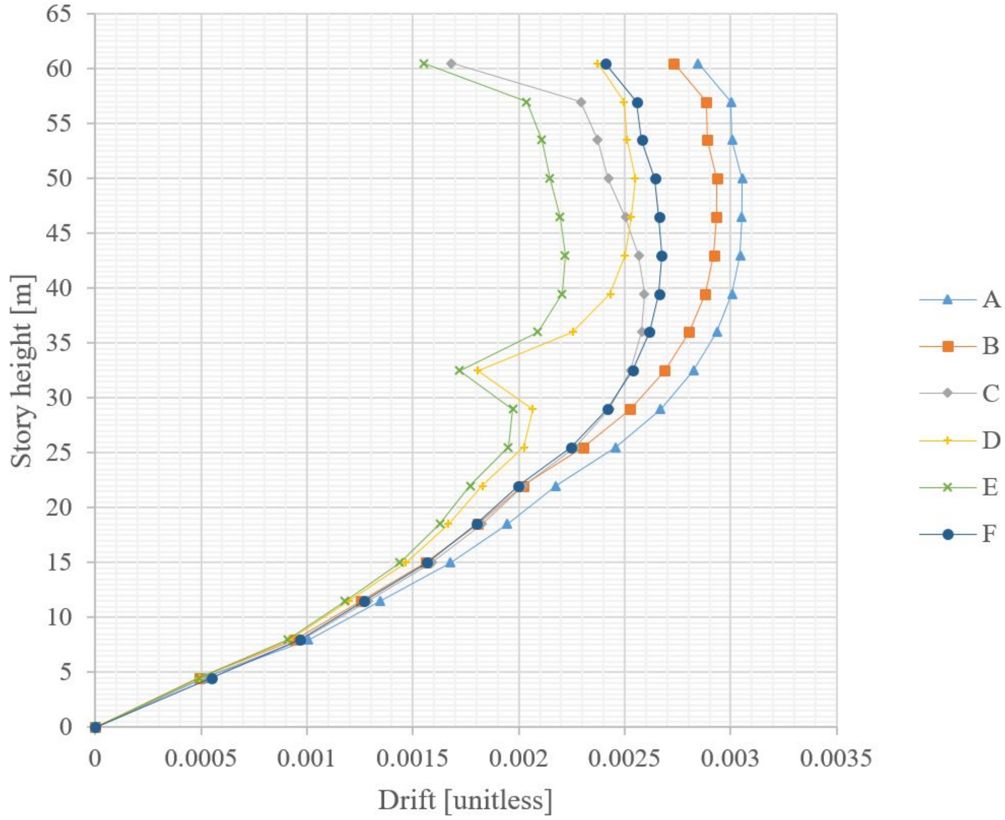

Figure 7. Story drift.

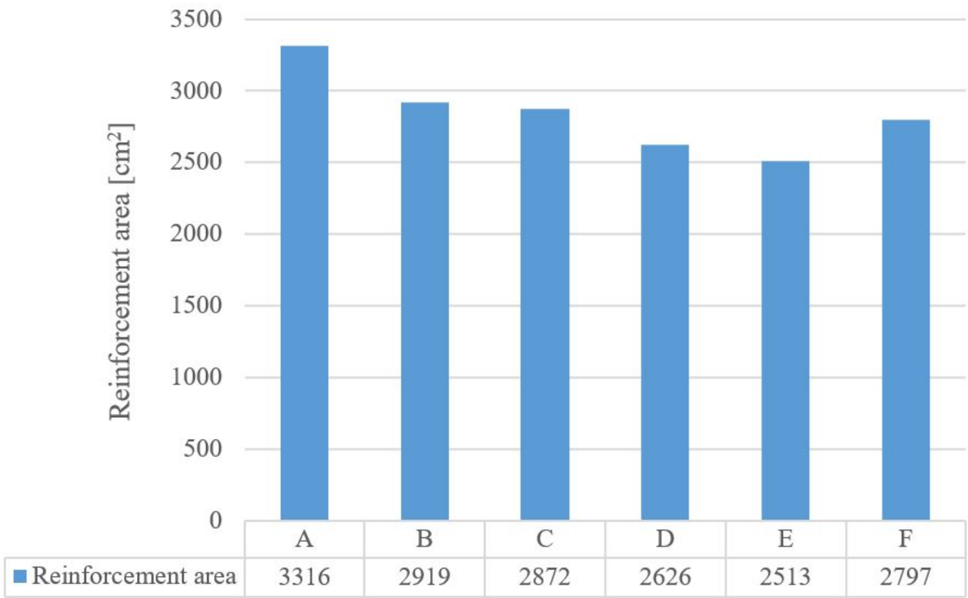

Figure 8. Required reinforcement area for the inner core: all models.

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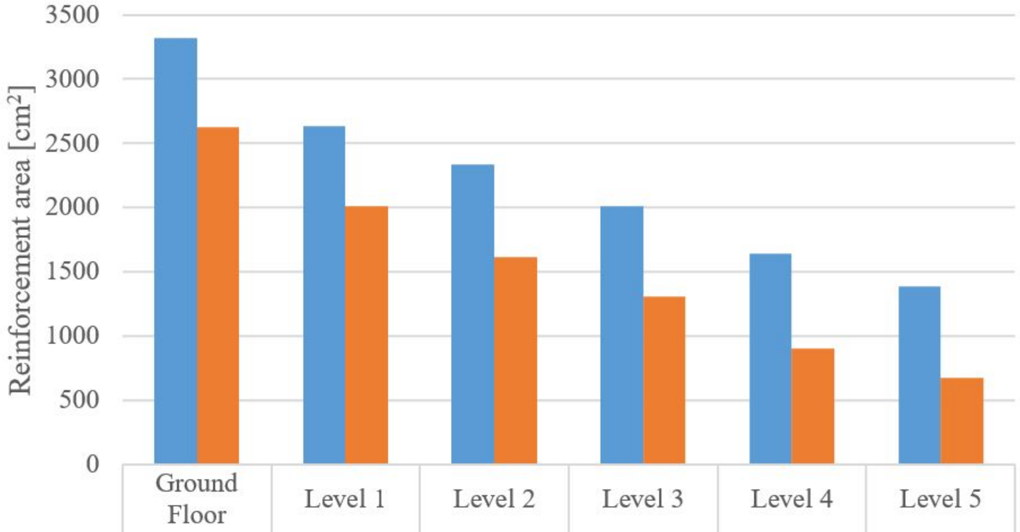

	Ground Floor	Level 1	Level 2	Level 3	Level 4	Level 5
A	3316	2638	2332	2006	1640	1388
D	2626	2014	1618	1308	906	675

Figure 9. Required reinforcement area for the inner core: models A and D.

The approximate quantity of steel required for one outrigger is 20 t. The reduction in reinforcement, of model D, for the first 6 levels of the structure is approximately 50.3 t. These reinforcement areas are presented in figure 9.

4. Conclusions

Structural engineers today have a great challenge to design tall buildings using cost effective solutions. At the same time, the architectural requirements became more demanding. Open office space and large windows are some of the requirements which impede the use of load bearing walls, braces, trusses or deep beams.

The structural systems analysed in this paper are usually used for buildings at least 40-50 stories tall. However, the results show that an important economy of reinforcement can be achieved by using these solutions even for buildings less than 20 stories tall. The amount of steel required for the outriggers does not exceed the amount of reinforcement saved in the inner core. The reduction of steel quantity for model D is significant (approximately 30.2 t). The main disadvantage of outriggers and truss belts is from the architectural point of view. Braces and trusses are used both in the office area and on the perimeter of the building, in the window area. However, this outcome might prove reasonable in compromising the architecture of a single level of the building with respect to the gain in material economy. Models C, D and E reflect the fact that the optimum position of one outrigger is at mid-height of the building. The efficiency of the outrigger placed at the middle of the building, in comparison to the placement at the top, is almost doubled as seen from the consumption of reinforcement (figures 8 and 9). The addition of 2 outriggers – one at the top and one at the middle of the building – show a very small improvement in comparison to the mid-height placement.

Model B shows a very small improvement. However, the use of steel profiles embedded in the inner core is beneficial for structures with very high axial forces in these areas. The main problem remains with the limited knowledge regarding the design of such structures, the load transfer and connections between steel and concrete.

The story drift does not exceed the allowable limit presented in P100-1/2013 for all models. However, a great reduction is observed for the models having outriggers (figure 7). The largest values were recorded, as expected, for the base model A and for model B having the hybrid column structural system.

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