Resistance of Steel-Concrete Composite Ceiling Beams of Multi-Storey Buildings

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Abstract. The paper deals with the problems of steel-concrete composite structural members, which are applied as the ceiling beams of multi-storey buildings, and composed of steel beam of hot-rolled IPE cross-section, concrete slab and profiled sheets, here having a function of a lost formwork. In the paper the theoretical comparative study of the resistance of the particular selected type of steel-concrete composite ceiling beam, among others in the connection with its deflections is presented. In the study the accent is especially paid to the link between ultimate limit state and serviceability limit state, in parallel together taking into account the beam span, cross-section dimensions (steel beam cross-section, concrete slab cross-section and profiled sheet) and grades of steel and concrete used in the mentioned load-carrying structure. The attention has been paid mainly to the resistance of the beam, subjected to the flexure effects, in relation to the corresponding deflections and in this connection to the evaluation of the reserve in the cross-section capacity, with regard to the economy and efficiency of the structural design. The study has been, among others, inspired by the static and structural design of the real building with steel / steel-concrete load-carrying structure, and evoked by the need of more effective and more economical design because of inappropriate large cross-sections in origin design.

1. Introduction
On the workplace of Department of Metal and Timber Structures of the Faculty of Civil Engineering at Brno University of Technology, the long-term attention is paid to the investigation of steel-concrete composite structural members and parts. The subjects of this research, in particular experimental one, are steel-concrete composite beams, as well as steel-concrete columns, for that ones the problems of the actual behaviour and objective ultimate load-carrying capacity of those structural members are investigated. The results of that experimental verification are then usually the basis for the subsequent elaboration and evaluation within the theoretical analysis, like as, for example, numerical modelling, analytical solutions, and so on.

Within the frame of so far performed experimental and theoretical analysis of steel-concrete composite beams, the attention has been, among other, paid to the application of high-performance concrete, especially concrete with higher tensile strength than usually, hereto glass-fibre-reinforced concrete, and its behaviour in zones of negative bending moments of the continuous beams. One of the main solved topics has been oriented towards the investigation of the contribution of glass-fibre-reinforced concrete to the resistance and the rigidity of the composite beam subjected to the negative bending moment. Some partial outputs of that research mentioned are informatively and illustratively presented in [2], for example.

This paper is focused on the problems of load-carrying capacity (resistance) of steel-concrete composite beams subjected to the positive bending moment, not from the viewpoint of their maximal load-carrying capacity (resistance), that means isolatedly from the real static and structural design, but from the viewpoint of the real cross-section dimensions of ceiling beams of multi-storey buildings.
dimensioned for the given specific loading actions, and further regarding not only ultimate limit state, but also the serviceability limit state, and taking into account the real results of the static and structural design, satisfying all the design conditions.

2. Basic general principles

Generally, the load-carrying capacity of steel-concrete composite beam can be determined on the base of plastic or elastic behaviour and the subsequent calculating procedures, arising from that – see, for example [1], [2], [5].

In the case of steel-concrete composite ceiling beams subjected to the positive bending moment, the utilization of the plastic behaviour and corresponding plastic calculation is usual, because almost always the neutral axis of steel-concrete cross-section lies in concrete slab, so that all the steel beam is subjected to tensile stress. If steel-concrete composite cross-section has – in average – for ceiling structures standard dimensions, and in addition, if the slab is concreted to profiled trapezoidal sheets, then a substantial part of concrete slab is mostly subjected to the compression, and both parts of the cross-section – steel and concrete – may be approximately comparably utilized. The typically known stress distribution for the plastic behaviour and above cited case is shown in Fig. 1. However, the deflection of steel-concrete composite beam has always to be determined exclusively using elastic behaviour and corresponding analysis.

![Figure 1. Typical stress distribution for plastic analysis of the beam resistance](image)

3. Comparative study

For the finding, which cross-sections of steel beam – considering various steel and concrete grades, real loading actions, but without changing the concrete slab thickness and profiled sheet dimensions – will be sufficiently efficient for the given beam span, regarding the usual practically used parameters, the comparative study has been performed.

In this comparative study, the following parameters, taken from the real ceiling structures of multi-storey buildings, have been used:

- steel grades of S235 and S355 in combination with two concrete grades (as follows);
- concrete grades given by “concrete classes” of C20/25 and C30/37;
- profiled trapezoidal sheets with the height of 40 mm (Hacierco 40S/160);
- whole concrete slab thickness of 110 mm;
- beam span in the range from 5 to 8 metres (with the step of 1 metre) or eventually 9 metres (in one case only);
- effective width of concrete slab 1.5 m or 1.25 m (eventually), in dependence on the beam span and usual distance between ceiling beams, calculated according to the European Standard EN 1994-1-1 Design of Steel and Concrete Structures [5];
- steel beam cross-sections of IPE type, in the range from IPE140 up to IPE270 (see following tables – Table 1, Table 2, Table 3, Table 4), according to the need following the static design of particular beams;
- for all cases the same uniform loads, corresponding with the usual loads of ceiling structures, taken from the European Standard EN 1991 Loading Actions.

Within the frame of this study, the static assessment has been performed for all considered cases. The aim of that assessment was to obtain such steel-concrete composite cross sections, which satisfy both the ultimate limit state, and serviceability limit state, within the usage of commonly available cross-sections.

The partial results of the performed study are shown in Tables 1 and 2 for steel grade of S235 with concrete C20/25 or C30/37, and Tables 3 and 4 for steel grade S355 with the same concretes.

From Tables 1 and 2 for steel grade of S235 it is evidently seen, that for the same dimensions of profiled sheet and concrete slab, the higher concrete quality leads to the higher resistance in bending only in the case of larger spans of 9 metres. Respectively, only for the span of 9 metres it is possible to apply the smaller dimension of the steel beam. In the case of the span of 9 metres the usage of better concrete leads to the decrease of steel beam, but at a price of the very small reserve in the cross-section resistance.

On the other hand, for the span of 9 metres and concrete C20/25 it may not be to use smaller steel profile than IPE270, although IPE240 exists.

**Table 1.** Partial results of comparative study – steel grade S235, concrete class C20/25

| beam span $L$ [m] | 5.00 | 6.00 | 7.00 | 8.00 | 9.00 |
|-------------------|------|------|------|------|------|
| effective width $b_{eff}$ [m] | 1.25 | 1.50 |      |      |      |
| cross-section (profile) | IPE140 | IPE160 | IPE180 | IPE200 | IPE220 | IPE270 |
| uniform load [kNm$^{-1}$] | 18.36 | 18.40 | 18.44 | 18.49 | 18.54 | 18.68 |
| bending moment $M_{Ed}$ [kNm] | 57.38 | 82.81 | 82.99 | 113.26 | 148.34 | 189.09 |
| moment resistance $M_{Rd}$ [kNm] | 64.23 | 83.16 | 103.24 | 127.40 | 154.45 | 230.26 |
| ratio $M_{Ed}/M_{Rd}$ | 0.89 | 1.00 | 0.80 | 0.89 | 0.96 | 0.82 |
| deflection $w$ [mm] | 8.0 | 11.8 | 9.0 | 12.8 | 17.1 | 16.3 |
| limit deflection $w_{lim}$ [mm] | 20 | 24 | 28 | 32 | 36 |      |
| ratio $w/w_{lim}$ | 0.40 | 0.49 | 0.38 | 0.46 | 0.53 | 0.45 |

**Table 2.** Partial results of comparative study – steel grade S235, concrete class C30/37

| beam span $L$ [m] | 5.00 | 6.00 | 7.00 | 8.00 | 9.00 |
|-------------------|------|------|------|------|------|
| effective width $b_{eff}$ [m] | 1.25 | 1.50 |      |      |      |
| cross-section (profile) | IPE140 | IPE160 | IPE180 | IPE200 | IPE220 | IPE270 |
| uniform load [kNm$^{-1}$] | 18.36 | 18.40 | 18.44 | 18.49 | 18.54 | 18.68 |
| bending moment $M_{Ed}$ [kNm] | 57.38 | 82.81 | 82.99 | 113.26 | 148.34 | 189.09 |
| moment resistance $M_{Rd}$ [kNm] | 65.98 | 85.34 | 106.35 | 131.79 | 160.48 | 194.87 |
| ratio $M_{Ed}/M_{Rd}$ | 0.87 | 0.97 | 0.78 | 0.86 | 0.92 | 0.97 |
| deflection $w$ [mm] | 8.0 | 11.8 | 9.0 | 12.8 | 17.1 | 17.1 |
| limit deflection $w_{lim}$ [mm] | 20 | 24 | 28 | 32 | 36 |      |
| ratio $w/w_{lim}$ | 0.40 | 0.49 | 0.38 | 0.46 | 0.53 | 0.60 |
Similarly, from Tables 3 and 4 for steel grade of S355 it is seen, that for the same dimensions of profiled sheet and concrete slab, the higher concrete quality does not significantly increase the bending moment resistance nor in the case of larger spans (of 8 or 9 metres). Respectively, for the spans of 8 and 9 metres the same dimensions of steel beam are needed, although the better concrete is used. As it turns out, from the viewpoint of practical usage of steel-concrete composite beams in ceiling systems of multi-storey buildings, steels and concretes of higher strengths in common are not so crucial in comparison with steels and concretes of normal strengths.

### Table 3. Partial results of comparative study – steel grade S355, concrete class C20/25

| beam span L [m] | 5.00 | 6.00 | 7.00 | 8.00 | 9.00 |
|-----------------|------|------|------|------|------|
| effective width b_{eff} [m] | 1.25 | 1.50 |      |      |      |
| cross-section (profile) | IPE140 | IPE160 | IPE180 | IPE200 | IPE220 |
| uniform load [kNm] | 18.36 | 18.40 | 18.44 | 18.49 | 18.54 |
| bending moment M_{Ed} [kNm] | 57.38 | 82.63 | 112.71 | 147.54 | 147.93 | 187.74 |
| moment resistance M_{Rd} [kNm] | 92.96 | 94.97 | 120.56 | 148.78 | 182.29 | 219.36 |
| ratio M_{Ed} / M_{Rd} | 0.62 | 0.87 | 0.93 | 0.99 | 0.81 | 0.86 |
| deflection w [mm] | 8.0 | 15.9 | 21.8 | 17.1 | 21.8 | 27.4 |
| limit deflection w_{lim} [mm] | 20 | 24 | 28 | 32 | 36 | |
| ratio w / w_{lim} | 0.40 | 0.66 | 0.78 | 0.53 | 0.68 | 0.76 |

### Table 4. Partial results of comparative study – steel grade S355, concrete class C30/37

| beam span L [m] | 5.00 | 6.00 | 7.00 | 8.00 | 9.00 |
|-----------------|------|------|------|------|------|
| effective width b_{eff} [m] | 1.25 | 1.50 |      |      |      |
| cross-section (profile) | IPE140 | IPE160 | IPE180 | IPE200 | IPE220 |
| uniform load [kNm] | 18.36 | 18.40 | 18.44 | 18.49 | 18.54 |
| bending moment M_{Ed} [kNm] | 57.38 | 82.63 | 112.71 | 147.54 | 147.93 | 187.74 |
| moment resistance M_{Rd} [kNm] | 96.97 | 98.30 | 125.55 | 155.86 | 192.31 | 233.12 |
| ratio M_{Ed} / M_{Rd} | 0.59 | 0.84 | 0.90 | 0.95 | 0.77 | 0.97 | 0.81 |
| deflection w [mm] | 8.0 | 15.9 | 21.8 | 17.1 | 21.8 | 34.9 | 27.4 |
| limit deflection w_{lim} [mm] | 20 | 24 | 28 | 32 | 36 | |
| ratio w / w_{lim} | 0.40 | 0.66 | 0.78 | 0.53 | 0.68 | 0.97 | 0.76 |

### 4. Conclusions

As generally known and here also seen from the results presented in tables above, in the case of the usage of usually produced hot-rolled profiles (hereto IPE), the needed bending moment resistance may be quite significantly influenced by the assortment of profiles. While in the case of small spans (about 5 metres, resp. less than 6 metres) the usage of steel-concrete composite beam is not very efficient, because the contribution of concrete has not been clearly demonstrated, in the case of larger spans (about 8 to 9 metres) the usage of steel-concrete composite cross-section may be very significant, because may lead to the decrease of the cross-section height, and thereby the reducing the overall ceiling structure height. How at least partially shown, the usage of better quality concrete does not probably have such meaning as often expected.
From the partial conclusions mentioned above, it may be stated, that investigated problematic still deserves attention, although it may be to seem, that many problems in this topic already have been solved, but with the development of better materials and new technologies (for example modern types and technological implementation of shear connectors) in civil engineering practice, there are still reserves in the static and structural design of steel-concrete composite beams, both in terms of more effective material utilization and more efficient cross-section configurations.

Because the comparative study mentioned above has been elaborated to the limited range of the parameters, it does not the predictive value, which could be more generalized, but it shows certain trends. For the more detailed analysis it will be needed to expand the range of parameters influencing the resistance of steel-concrete composite beams, of course with respect to the practical useability in the real structures.

5. References
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