# Composite Steel-Concrete Bridges with Double Composite Action

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**Abstract**

Composite bridge decks usually consist of a steel structure that works together with a top concrete slab, which forms the road, rail or pedestrian platform. This structural solution has been adopted over the last 50 years in small span bridges, as well as in medium and long span bridges.

Composite steel-concrete decks are particularly well designed to work in mid-span regions. The top concrete slab withstands the compressive forces while the bottom steel structure copes with the tensile forces generated by the positive bending moments. However, these composite decks are less efficient for the negative bending moments over the intermediate support cross-sections. On one hand, the slab of concrete tends to crack under the tensile forces, and significant quantities of reinforcing are needed to control this effect. On the other hand, the steel structure below needs stiffeners to ensure its high resistance to compression, without local or global instability.

Decks with double composite action are a recent development in this structural solution, in which a second slab of concrete is added to the bottom flange of the steel structure. The aim is to ensure stability of the steel structure and increase its resistance, improving the functioning of the cross-sections over the intermediate supports.

Results indicate that decks with double composite action use less structural steel per deck area unit; have higher resistance to bending moments and better response to torsional effects when compared with a conventional composite steel-concrete deck, even though the deck section is heavier.

*Key words*: Composite steel-concrete bridges; Decks with double composite action; Box-girder deck; Twin plate girder deck.

**1 – Introduction**

Composite steel-concrete bridges usually present design difficulties in the cross sections over the internal supports due to the high compression generated by the negative bending moments in the bottom flange. This difficulty can be solved by adding a bottom concrete slab, whose function is to prevent the local instability of the bottom steel flange and increase its resistance. These decks are designated "composite steel-concrete decks with double composite action". This work aims to study bridges that have composite steel-concrete decks with double composite action, to identify the advantages and disadvantages of their use, and evaluate their in-service behavior and ultimate resistance.

**2 – Composite Steel-Concrete Decks**

Over the years, a large number of bridges and overpasses have been built with pre-stressed concrete decks. At the same time, bridges with all steel decks have always been very well accepted as a solution, for railway decks and for very long suspension and cable-stayed decks. Over the past 50 years, the number of bridges built with composite steel-concrete decks, composed of a concrete slab interacting with a steel structure, has been gradually increasing in several countries.

The combined use of steel and concrete in bridge decks aims to take advantage of the best features of each material. This means combining the high compressive strength of concrete and the good tensile performance of steel. The choice between a pre-stressed concrete deck or a composite steel-concrete deck is influenced by factors such as spans, the building process, geotechnical conditions, economic aspects (construction and maintenance costs), construction period, aesthetics and landscaping.

A composite steel-concrete bridge generally has the following main advantages over a pre-stressed concrete bridge [1]:

- Lower self-weight of the deck;
- Simpler construction methods;
- Faster rate of construction.

But there are some important disadvantages:

- Normally a higher initial cost;
- Higher maintenance costs;
- Superior building technology.

The commonest of the various composite deck solutions are twin plate girder decks and box-girder decks.

### 2.1 – Twin plate girder decks

This structural solution consists of a concrete slab, usually made of reinforced concrete, supported by a grid composed of longitudinal main plate girders and steel transverse secondary beams. It is a competitive solution for small and medium spans. Hot-rolled steel sections may be used for small spans. For longer spans for reasons of structural efficiency and simplicity of construction, decks with two steel welded plate girders, usually called twin plate girder decks, are generally adopted.

### 2.2 – Box girder decks

Because of their structural efficiency, in particular their good torsional behavior, box girder decks are commonly used for long-span bridges, curved bridges and situations where it is important to maximize the slenderness. This solution has the following advantages over the twin plate girder bridges:

- Higher torsional rigidity, because it is a closed section;
- Bottom flange often wider, leading to greater bending moment resistance;
- The interior space makes maintenance and service's installation easier.

## 3 – Composite Steel-Concrete Decks with Double Composite Action

The double composite action seeks to improve the structural behavior of a steel-concrete composite bridge, particularly in the sections over the interior supports. In these sections, the applied bending moments (negative by convention) produce stress in the materials, steel and concrete, such that they are structurally less efficient. In fact, the negative bending moments cause tensile stress in the upper concrete slab, which usually tends to crack prematurely under the action of dead loads; these forces need be absorbed by the reinforcement and the upper steel flange. However, the compression that is developed in the lower steel flange is usually more of a problem. In conventional composite solutions, this compression can lead to phenomena of lateral instability, which require the use of very thick flanges and / or stiffeners and bracing in the deck sections near the internal supports.

In keeping with the concept of placing each material where it is more efficient in structural terms, the concept of double composite action is the addition of a second concrete slab at the bottom flange of the deck cross-section near the supports, working with the bottom steel flange to resist the negative bending moments. At the same time the lower concrete slab gives the required stability to the bottom flange, with no need for additional local plate stiffeners or bracing systems. It is intended, with this solution, to achieve the following improvements, relative to a conventional composite solution [2]:

- Increased resistance to negative bending moments;
- Reduction of bottom steel flange thickness;
- Reduction (or elimination) of instability at the bottom flange and web of the steel section;
- Fewer stiffeners needed;
- Better torsional behavior;
- Better fatigue behavior;
- Less deck deformation.

The drawbacks of this solution compared with conventional composite decks are the expected longer construction time due to the implementation of the lower slabs, and the higher dead load of the structure, which may need more expensive bearing supports, piers and foundations. The total cost of the solution may be another important disadvantage.
Yet, the concept of double composite action is not entirely new. The first bridge using this structural solution was the Ciérvana bridge, built in Spain in 1978 [3]. Since then, the use of this technology had been progressively increasing in many countries and in different directions.

### 3.1 – 'Strict box' girder decks

This structural solution was first designed by Julio Martinez Calzón [4], and it resulted from applying the principle of double composite action to a conventional twin plate girder deck.
A recent example of this deck type is the Arroyo de las Piedras viaduct. Included in the Spanish High Speed Railway Line project, and completed in 2005, it was the first of several high-speed railway bridges in Spain to use a composite steel-concrete deck. Located in Cordova-Malaga section of line, the deck is a continuous beam with spans of 50.4 x 17 m + 63.5 m + 44.0 m + 35.0 m = 1 208.9 m (Fig. 1).
The deck cross-section (Fig. 2) is 3.85 m deep and the top slab is 14 m wide. The bottom slab is extended along the entire deck, being thicker in sections close to the piers.

Fig. 1 – View of underside of Arroyo de las Piedras viaduct

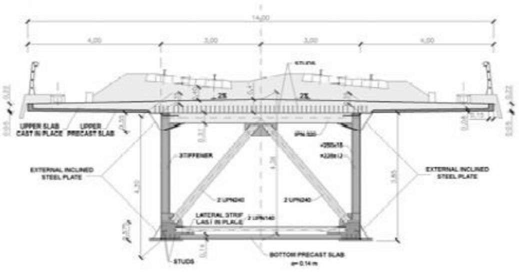


Fig. 2 – Cross-section of Arroyo de las Piedras viaduct [4]

3.2 – Box-girder decks

The double composite action has been used in bridges with several section types, but it is in box-girder sections that this structural solution has been most often used. One recent example is the viaduct over the A5 highway, in Lisbon (Fig. 3), completed in 2006, has two spans of 43 m + 41 m = 84 m. Due to the gauge restrictions, the cross-section, in a three cell box-girder is only 1.69 m deep. The top slab 18.40 m wide is connected to three boxes (Fig. 4). The double composite action is obtained by the addition of a 0.20 m thick bottom concrete slab extending for a length of 4 m on each side of the deck cross-section's central support [5].

Fig. 3 – Views of the viaduct over the A5, in Lisbon

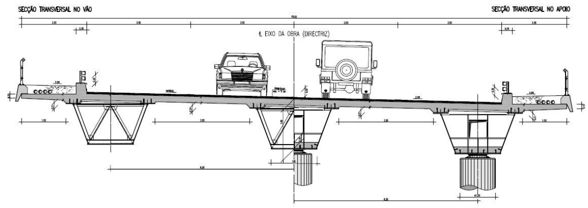

Fig. 4 – Deck mid-span and support cross-sections of viaduct over A5 [5]

**4 – Bending Analysis**

The strength and in-service behavior of the following two composite decks was analyzed, with and without the double composite action: case study #1) southern access viaduct of Alcácer bridge over Sado river – railway twin girder deck; and case study # 2) bridge BO3 on the new Antwerp ring road – road box girder deck. In each case, the assessment was made for the proposed solution and an alternative solution, thereby considering the conventional composite solution and a double composite action alternative. The actions and safety verifications were based on current regulations and the Eurocodes.

4.1 – Case Study #1

The deck cross-section is a conventional composite twin plate girder [6]. The concrete slab is 15.70 m wide and of variable thickness: 0.40 m over the steel top flange and 0.20 m in the slab panel min-span and at the cantilever tips. The steel beams, 2.60 m deep, are connected to the slab by stud connectors, forming a total 3 m deep deck. Though the bridge deck is much longer, only the first 4 spans, each 45 m long, were modeled.
For this case study, in addition to this built conventional solution, alternative A (Fig. 5), an alternative solution was also studied, alternative B (Fig. 6), which has double composite action in the deck cross-sections over the internal supports. For this study a 0.25 m thick lower concrete slab was assumed in these sections, and the lower flanges were assumed to be less thick.

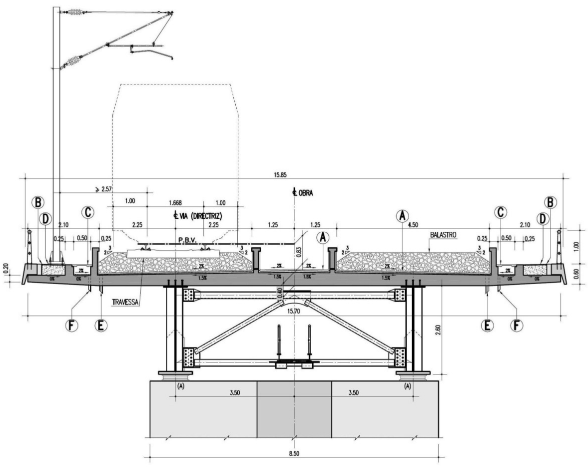

Fig. 5 – Case study #1: cross-section over piers – alternative A [5]

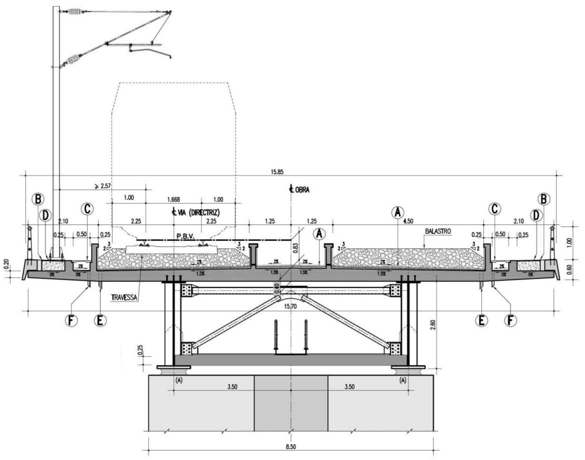

Fig. 6 – Case study #1: cross-section over piers – alternative B

| | 1st span | 1st internal pier | Typical span | Typical pier |
|---|---|---|---|---|
| Msd (kNm) | 148812 | -183398 | 100904 | -148068 |
| Mrd (kNm) | 188500 | -193500 | 149500 | -166500 |
| Mrd / Msd | 1.27 | 1.06 | 1.48 | 1.12 |

Table. 1 – Case study #1: Bending moments – alternative A (kNm)

| | 1st span | 1st internal pier | Typical span | Typical pier |
|---|---|---|---|---|
| $M_{sd}$ (kNm) | 147877 | -188385 | 99801 | -150434 |
| $M_{rd}$ (kNm) | 188500 | -253500 | 149500 | -221000 |
| $M_{rd}$ / $M_{sd}$ | 1.27 | 1.35 | 1.50 | 1.47 |

Table. 2 – Case study #1: Bending moments – alternative B (kNm)

| δ (m) | 1st span | Typical span | $δ_{máx}$ = L/600 |
|---|---|---|---|
| Alternative A | 0.037 | 0.033 | 0.068 |
| Alternative B | 0.036 | 0.031 | |

Table. 3 – Case study #1: Vertical deflections – alternatives A and B (m)

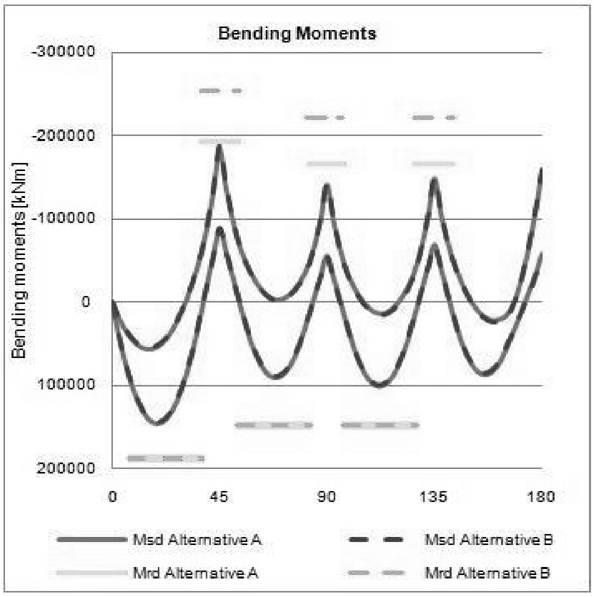


Fig. 7 – Case study #1: Bending moments diagram – alternatives A and B (kNm)

Comparing the two solutions, the increase in the bending moment's resistance at deck cross-section on the 1st internal support was about 31% (from 193 500 kNm to -253 500 kNm), while in the other internal support sections the increase was about 33% (from -166 500 kNm to -221 000 kNm).

With respect to the vertical deck deflection (Table 3), it is clear that the introduction of double composite action reduces the deformability of the deck. The reduction was about 3% on the 1st span and about 7% in the typical internal spans, though in absolute terms it represents only a reduction of 1 to 2 mm.

The total weight of structural steel per square meter of deck, with a 15% of increase for stiffeners and bracing systems, was 176 kg/m$^2$ for alternative A and 167 kg/m$^2$ for alternative B. This difference is only due to the reduction of the bottom flange thickness in the sections with double composite action. But the concrete deck self-weight rose by almost 10%, from 825 kg/m$^2$ in solution A to 906 kg/m$^2$ in solution B, which corresponds to a total increase in the self-weight of the composite deck of 7% with the introduction of the bottom slab.

## 4.2 – Case Study #2

This case study is of a deck with three spans of 64 m + 112 m + 64 m = 240 m. The proposed design solution (alternative B) with double composite action was analyzed, and a conventional composite solution (alternative A), was also studied. For this case, the designed bottom concrete slab of support sections was replaced by a thicker bottom steel flange stiffed by five instead of three longitudinal stiffeners.

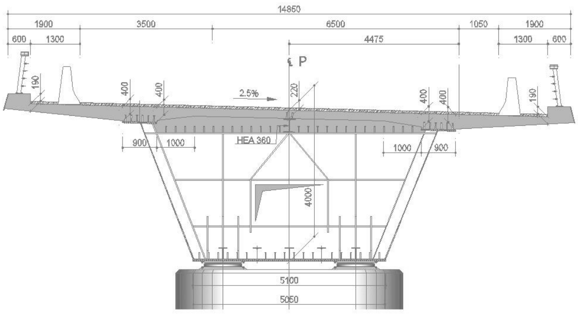

Fig. 8 – Case study #2: cross-section over piers – alternative A

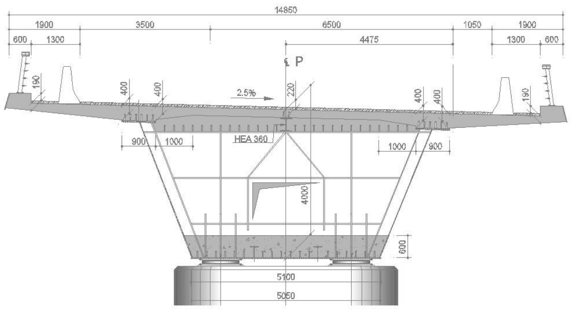

Fig. 9 – Case study #2: cross-section over piers – alternative B [5]

| | Lateral span | Internal pier | Internal span |
|---|---|---|---|
| $M_{sd}$ (kNm) | 83522 | -381703 | 251588 |
| $M_{rd}$ (kNm) | 248500 | -412000 | 324500 |
| $M_{rd}$ / $M_{sd}$ | 3.07 | 1.08 | 1.26 |

Table. 4 – Case study #2: Bending moments – alternative A (kNm)

| | Lateral span | Internal pier | Internal span |
|---|---|---|---|
| $M_{sd}$ (kNm) | 84836 | -372409 | 255874 |
| $M_{rd}$ (kNm) | 248500 | -397000 | 324500 |
| $M_{rd}$ / $M_{sd}$ | 2.93 | 1.07 | 1.27 |

Table. 5 – Case study #2: Bending moments – alternative B (kNm)

| δ (m) | Lateral span | $\delta_{máx}$ = L/1000 | Internal span | $\delta_{máx}$ = L/1000 |
|---|---|---|---|---|
| Alternative A | 0.012 | 0.064 | 0.046 | 0.112 |
| Alternative B | 0.012 | | 0.046 | |

Table. 6 – Case study #2: Vertical deflections – alternatives A and B (m)

The resistant bending moment of the deck cross-sections over the piers , for alternative A, is near 4% higher than the resistance in the solution with double composite action (alternative B), 412 000 kNm and 397 000 kNm.

With respect to vertical deck deformation, both solutions presented very similar values.

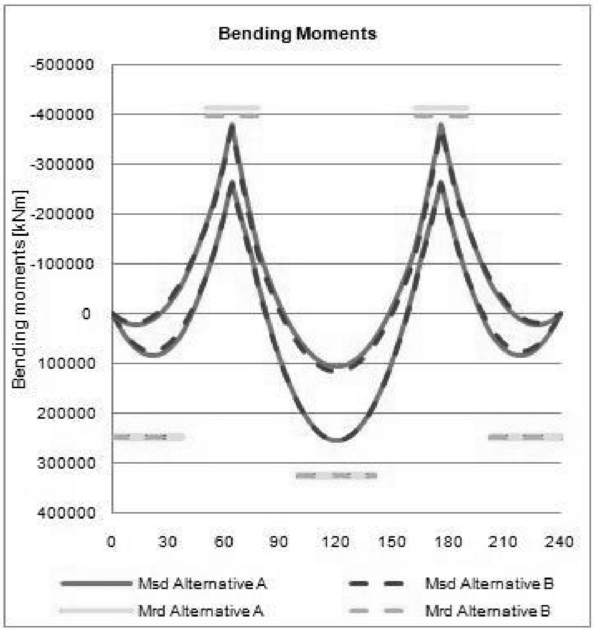


Fig. 10 – Case study #2: Bending moments diagram – alternatives A and B (kNm)

In terms of the amount of structural steel, and considering a 15% increment for stiffeners and the vertical bracing system, alternative A uses 252 kg/m$^2$ while the solution B needs about 222 kg/m$^2$. In relative terms, the difference is about 12% and it is due to the considerable reduction of the thickness of the bottom steel flange and reduction of stiffeners in alternative B, as a result of the introduction of the bottom concrete slab. However, the self-weight of concrete rose by 13%, from 750 kg/m$^2$ in alternative A to 864 kg/m$^2$ in alternative B. The total self-weight of the composite deck increases nearly 8% with the introduction of the bottom slab at the internal support sections.

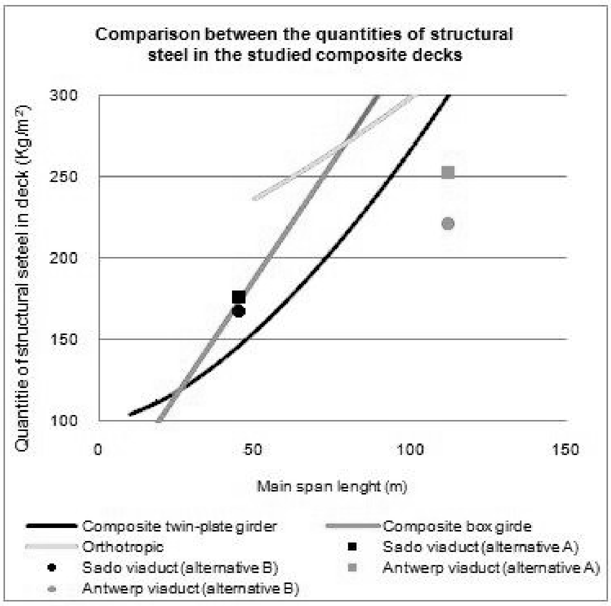


Fig. 11 – Comparison of the amounts of structural steel in the composite decks studied

### 5 – Torsion Analysis

The torsional behavior was assessed for the twin plate girder deck in case study #1 – railway access viaduct to Sado bridge. The study compared three different solutions: the design solution – alternative A – a conventional composite twin plate girder deck; an alternative solution with double composite action only at deck cross-sections over the supports – alternative B – similar to the solution B analyzed in 4.1; and a third solution, also with double composite action, but with the bottom concrete slab extended to the entire deck – alternative C – similar to the design solution adopted in the viaduct Arroyo de las Piedras.

In order to simulate the proper torsional behaviour, three-dimensional finite element models were used.

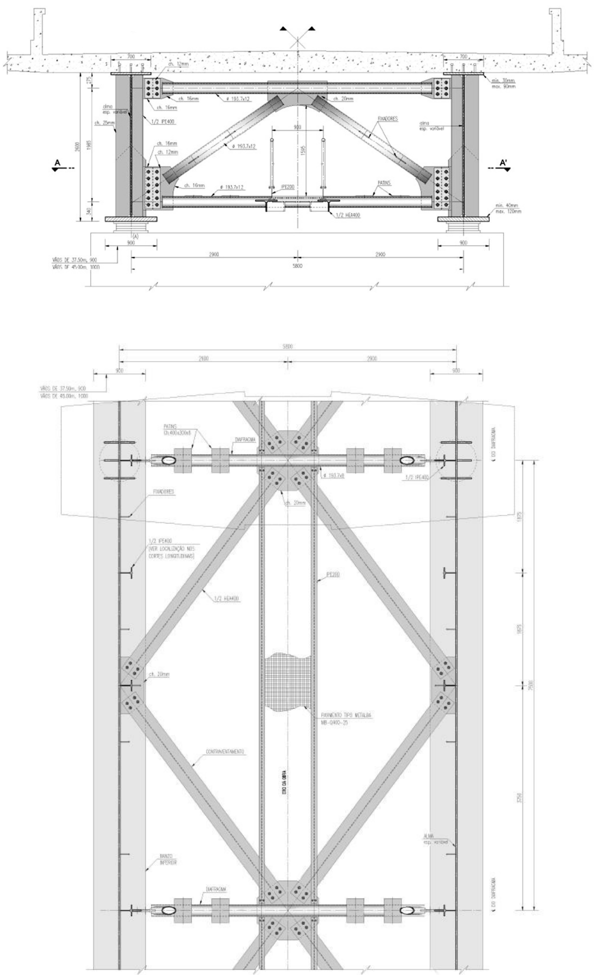

Fig. 12 – Typical cross-section and transverse bracing system [5]

An asymmetric load scenario duo to one train circulation is considered to obtain the highest torsional effect on the deck.

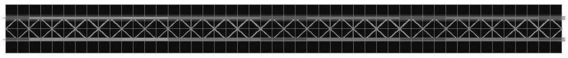

Fig. 13 – Bottom deck view – alternative A

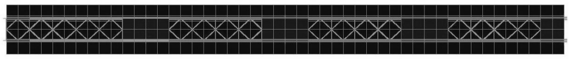

Fig. 14 – Bottom deck view – alternative B

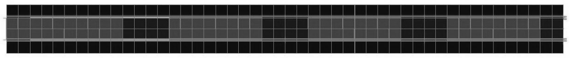

Fig. 15 – Bottom deck view – alternative C

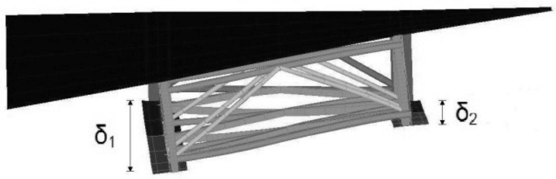


Fig. 16 – Deformed deck shape due to an asymmetric train load – alternative A

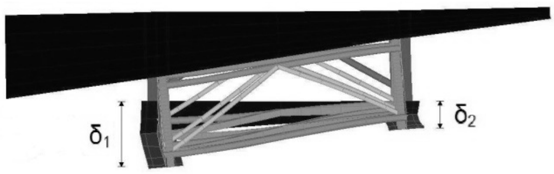


Fig. 17 – Deformed deck shape due to an asymmetric train load – alternative B

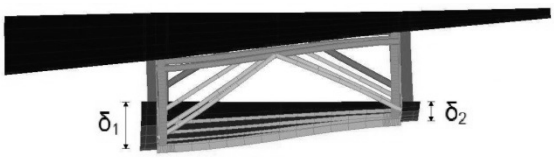


Fig. 18 – Deformed deck shape due to an asymmetric train load – alternative C

| | Alternative A | | Alternative B | | Alternative C | |
|---|---|---|---|---|---|---|
| δ (mm) | $\delta_1$ | $\delta_2$ | $\delta_1$ | $\delta_2$ | $\delta_1$ | $\delta_2$ |
| 1st span | 30.9 | 10.8 | 29.5 | 11.8 | 21.5 | 8.8 |
| Typical span | 27.2 | 9.4 | 25.2 | 10.6 | 18.4 | 7.8 |

Table. 7 – Comparison of vertical deflections of each beam – alternatives A, B and C (mm)

| | Alternative A | Alternative B | | Alternative C | |
|---|---|---|---|---|---|
| | $\theta_A$ (°) | $\theta_B$ (°) | $\theta_B/\theta_A$ | $\theta_C$ (°) | $\theta_C/\theta_A$ |
| 1st span | 0.104 | 0.086 | 83% | 0.024 | 28% |
| Typical span | 0.084 | 0.061 | 73% | 0.009 | 11% |

Table. 8 – Comparison of deck torsion angle at middle-span – alternatives A, B and C (°)

Slightly lower vertical displacements and rotation in middle-spans were obtained, from the alternative A to alternative B. However, comparing the alternatives A and C, it is clear that the reductions of these values are more obvious.

**6 – Concluding Remarks**

This study have shown that when a second concrete slab is introduced at the bottom flange level of the support cross-sections of conventional twin plate girder decks or box-girder decks, there is a reduction of about 10% of the total quantity of steel used on the deck, and the resistance of these cross-sections to bending moments is maintained or increased. This reduction of the amount of steel is essentially due to the removal of the bottom flange stiffeners and a part of the longitudinal bracing system required, and to decreasing of the bottom steel flange thickness, in particular for box-girder sections.

This solution, when extended to middle-span areas on twin plate girder decks, also significantly improves the torsional rigidity of the deck, and therefore less cross-bracing is required and there is less torsional deformability for the action of live asymmetric loads.

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