Assessment of failure and malfunctions in steel bridges

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Summary

The verification of existing steel structures especially steel bridges is in present one of the main problems of the structural engineers. The majority of existing railway steel bridges that have been built at the turn of the last century are riveted structures. Today many of these structures have already achieved a considerably age; therefore the establishment of the remaining fatigue safety of these structures is one of the most important tasks of contemporary society. Many of these bridges are still in operation after damages, several phases of repair and strengthening. The problem of these structures is the assessment of the present safety for modern traffic loads and the remaining service life. An assessment of safety may be required as a result of different observations like: displacements, cracks, vibrations, corrosion, etc. In the classical accepted assessment based on the damage accumulation theory, the main considered factors are the following: applied stresses and stress ranges, geometry of the details and number of stress cycles. The paper presents the Romanian Methodology in this field with some case studies.

Keywords

Existing steel bridges, observations, verification, safety.

Background

The infrastructure in Romania and in other East – European countries has an average age of about seventy to ninety years. Many of these structures, particularly railway bridges, have already achieved an age of ninety, hundred or even more years and are still in operation after damages, several phases of repair and strengthening. To maintain these structures is one of the most important tasks of our society. Replacement with new structures raises financial, technical and political problems.

Today, the budget of the administration and the owners (i.e. the railways and highway companies) get smaller. In consequence it is necessary to invest the available money where there will be the greatest benefit. Therefore, those responsible for the decisions need information about the safety of the structure, the remaining life, the costs for maintenance etc. *Nobody will take the responsibility for failure of a structure as a result of budget restrictions.* The public highway network in Romania has a length of 153 014 km; from a total number of 3131 bridges only 81 (≈ 3 %) are steel bridges. The explanation for the reduced number of steel bridges is given by the absence of motorways (only 113 km). During service, bridges are subject to wear. In the last decades the initial volume of traffic has increased. Therefore many bridges require an inspection. The examination should consider the age of the bridge and all repairs, the extent and location of any defects etc.[1] A continuous maintenance, which generally must increase in time, is important in order to assure the safety in operation of the existing structures.

Problem statement

Carefully inspection of the structure is the most important aspect in evaluating the safety of the bridge. On the accuracy of the in situ inspection depends the level of evaluation. The check of existing structures should be based on the complete bridge documentation (drawings with accuracy details, dimensions and cross sections of all structural elements, information about structural steel, stress history. However, in many cases these documentations are incomplete or missing. But these information can be recovered due to the carefully investigations and inspections of the structures, experimental determination of the material characteristics and stresses in structural elements, full scale in situ tests (static and dynamic), calibration of structure and spatial static analysis. The data material used in this paper were taken from literature, where defects and analysis of their causes have been presented mostly based on investigation work performed by others.

Present verification methodology

The assessment of the bearing capacity of existing bridges is a complex matter. Beginning with 1986, a systematic checking of bridges built in the last century or at the beginning of this century has begun in Romania. Based on the accumulated experience and according to the UIC (Union Internationale des Chemins de Fer) cards [2], and German Standard [3], a methodology was proposed; it includes the following stages:

STEP 1: estimation of the loading capacity of the structure based on a detailed inspection; analysis of drawings, inspection reports, repairs, reinforcements, analysis of the general behavior of the bridge (displacements, vibrations, corrosion, cracks). In this phase the stresses in the structure can be calculated with the usually simplified hypothesis;

STEP 2: the accurate determination of the stresses in the structure and of the remaining safety of the elements. This phase includes: tests on materials, computer aided analysis of the space structure, remaining safety calculated on the base of the real time - stress history;

STEP 3: in situ static and dynamic tests.

This methodology adopted by the Romanian standard is illustrated in Figure 1.

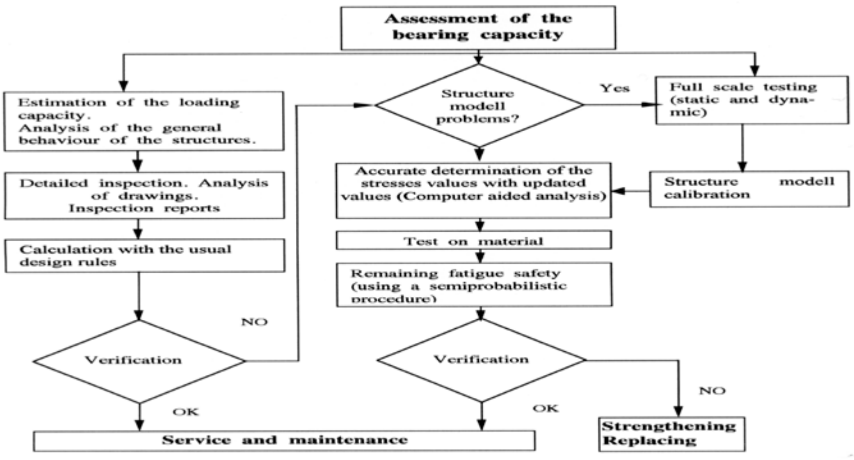

Figure1: Methodology of the Romanian standard SR 1911-98 [4]

It must be noted that the cumulative damage induced by different patterns acting on the structure is given by the Palmgreen - Langer - Miner rule. For the bridges situated on the principal railways, the real time - stress history was established by using the documentation of the administration. Generally, to establish the traffic in the past (sometimes even more than 100 years) is not very easy. With the traditional damage accumulation method a constant increase of the damage can be noticed. Observation: the first step in the identification of critical details are the study of documents (like drawings, repairs, strengthening etc.) followed by detailed inspection of the structure. It is important to evaluate the behavior of the bridge under service conditions (displacements, vibrations, corrosion, cracks, etc). A special attention must be paid to stresses, which have not been taken into consideration during the calculation of the structure (out of plane stresses, torsion stresses, etc.

Technical condition of existing bridges

Mostly the bridges are simple supported girders (rarely continuous); according to the cross section there are deck or trough bridges. The majority of them are plate or truss girder bridges; other constructive systems like twin girders or bundle of rails can also be noticed.

However, from the overall examination of a large number of bridges many defects can be pointed out. The defects are widespread, having a heterogeneous character from the point of view of location, development and development tendency; their amplification was also due to the climate and polluting factors that caused the reduction of the cross section due to corrosion. Statistically, in 283 from among 1088 welded bridges, and in 356 from among 3201 steel riveted bridges cracks were detected and repaired. In Table 1 some typical defects in stringers, cross girders, main girders wind bracings and orthotropic deck and their repair are presented [5].

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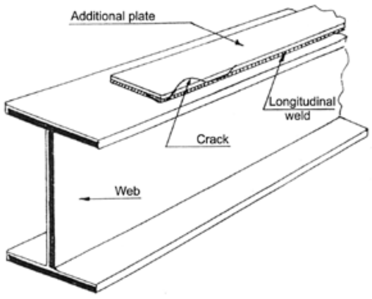
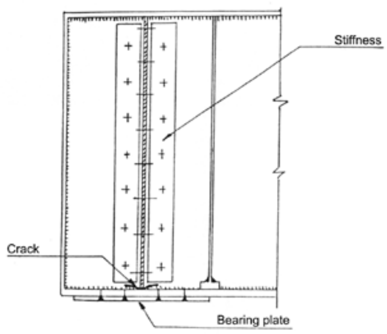
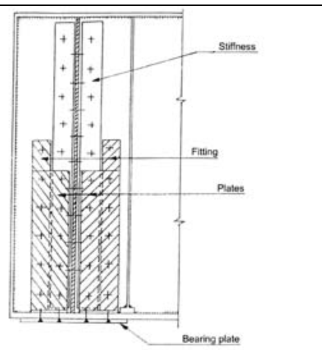
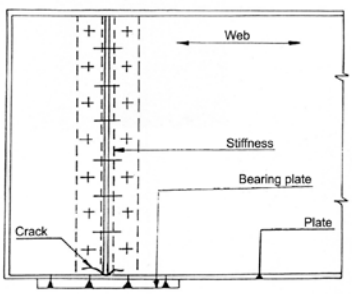
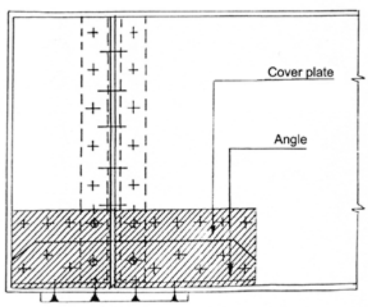
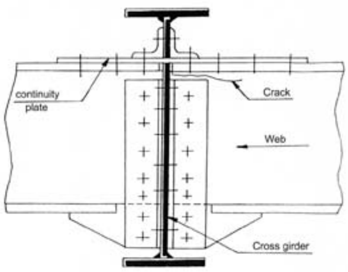
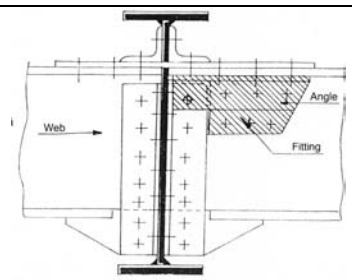
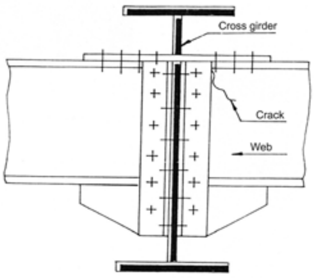
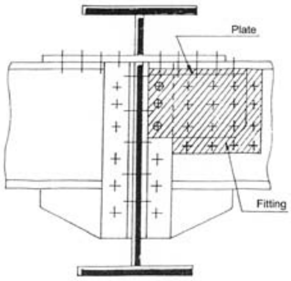
Main girder		⇨ Grinding ⇨ New additional plate ⇨ Observation
Main girder		
Main girder		
Stringer		

Stringer		
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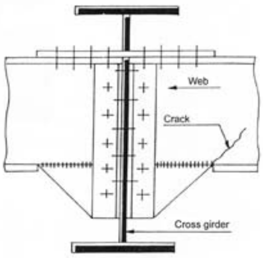
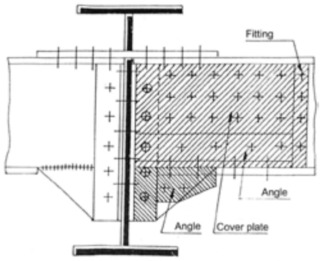
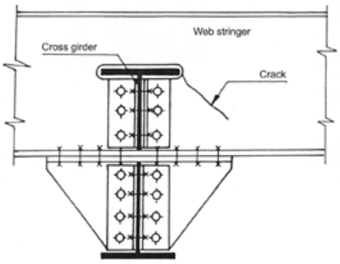
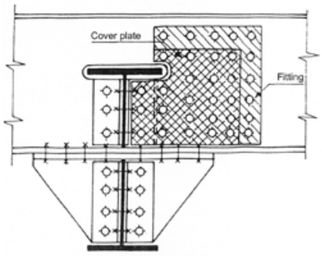
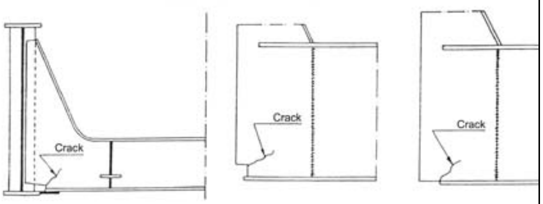
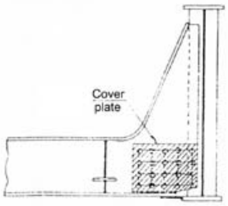
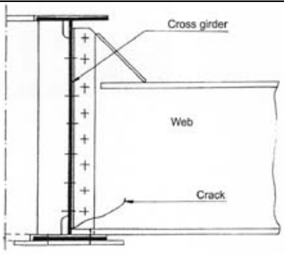
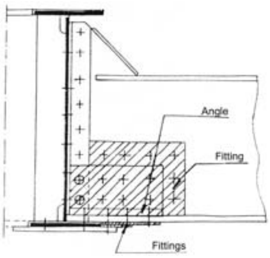
Stringer		
Stringer		
Cross girder		
Cross girder		

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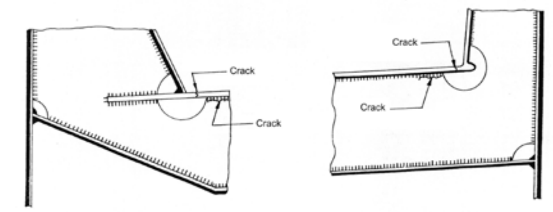
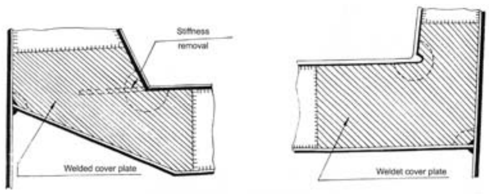
<tr><td>Ortho-tropic deck</td><td>
</td><td>
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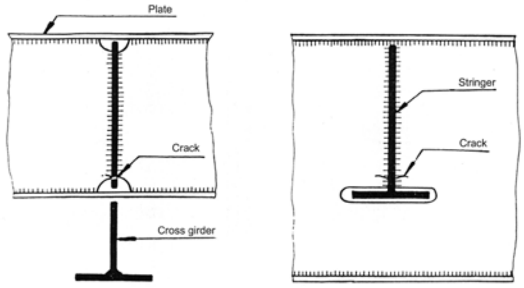
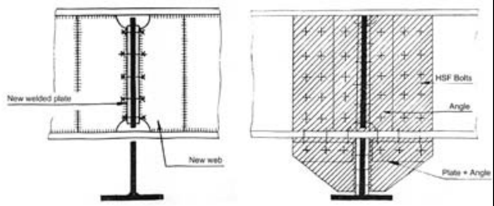
<tr><td>Ortho-tropic deck</td><td>
</td><td>
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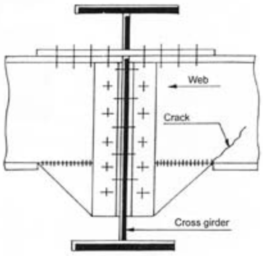
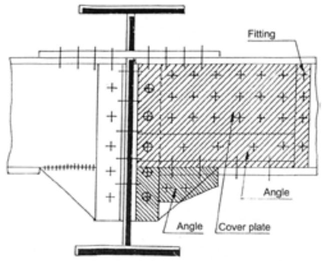
<tr><td>Stringer</td><td>
</td><td>
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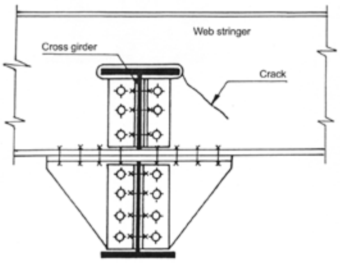
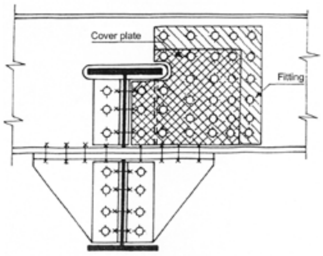
<tr><td>Stringer</td><td>
</td><td>
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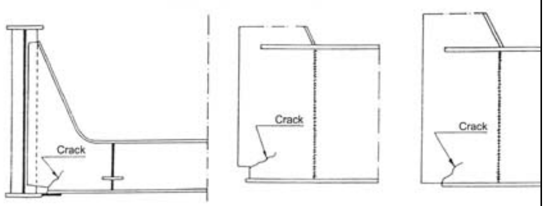
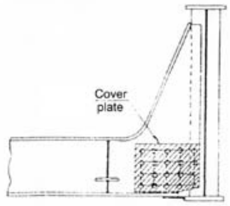
<tr><td>Cross girder</td><td>
</td><td>
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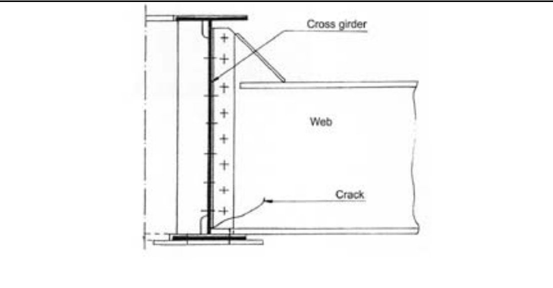
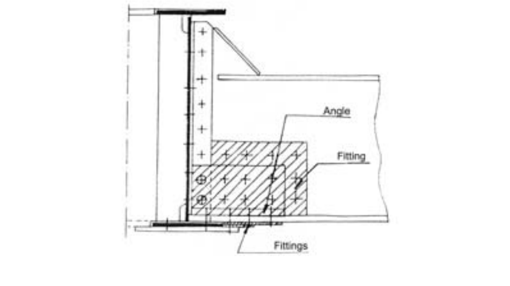
<tr><td>Cross girder</td><td>
</td><td>
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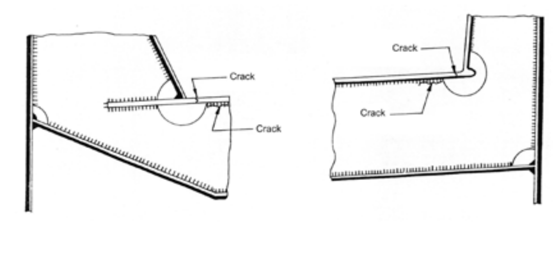
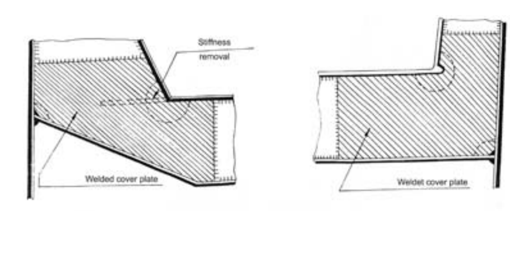
<tr><td>Ortho-tropic deck</td><td>
</td><td>
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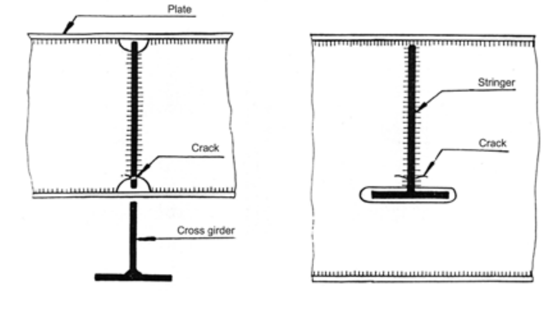
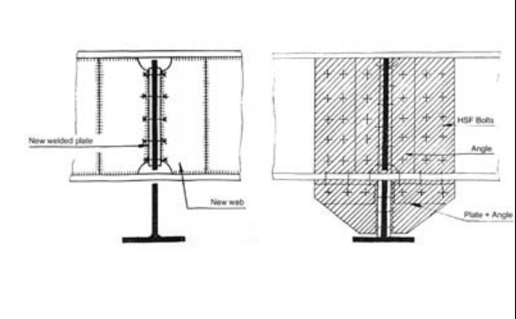
<tr><td>Ortho-tropic deck</td><td>
</td><td>
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Table 1: Typical defects in welded steel bridges

Recommendations

With the traditional static analysis (the space system is divided in plane elements), stresses are normally over-estimated. In order to calibrate the static model measurements on the bridge are useful. In many cases the structural capacity of these bridges is still satisfactory, as a result of a conservative design at the time.

The verification of more than 25 bridges leads to some worth mentioning general remarks:

- ✓ Materials, loadings and static models are defined in a deterministic way, the fatigue safety by sem iprobabilistic procedures.
- ✓ The characteristic values for the material resistance are often very conservative.
- ✓ Using the more realistic actual loads (instead of the loads given in different codes) the remaining fatigue life can be extended.
- ✓ The usual stress analysis is 10 – 25 % higher than the measured values in the structure; concerning the fatigue loads this means an extension of the expected remaining life by a factor of 1,5 – 2,5.
- ✓ Corrosion has an influence on the fatigue resistance curve.

- ✓ Steel bridges are ductile structures; before failure will occur, the structure must have considerable deformations. Deformations are the best pre-warning system.

The calculation of remaining fatigue life is normally carried out by a damage accumulation calculation. The cumulative damage caused by stress cycles will be calculated; failure criteria will be reached.

The presence of cracks in structural elements modifies essentially their fracture behaviour. Fracture, assimilated in this case as crack dimensions growth process under external loadings, will be strongly influenced by the deformation capacity of material. This capacity is reflected by the two practically noticed fracture modes, namely: the ductile and the brittle fracture. A definition of these fracture modes, used in fracture mechanics analysis applicable to bridges, is presented in [6]. It must be emphasized that the final failure of the element is determined by the predominant stress - strain state which in turn, depends on the element thickness, loading rate and temperature. In this direction, for the safe and economic evaluation of the remaining fatigue life of existing structures, a damage accumulation based on fraction mechanics can be developed. The FM approach has acceleration in damage increase; with increasing damage a smaller stress range contribute This evaluation requires the establishment of a fracture criterion for the cracked element and the adopting of maximum admissible crack dimensions, taking into account the deformations / displacement of this element under the service loads the damage increase.

Outlook to further research

- ✓ For a reliable assessment of existing bridges a unified methodology is needed including damage accumulation method and fracture mechanics concepts.
- ✓ It is also important to mention that with introduction of the Structural Eurocodes the technical rules and regulations are unified, the technical barriers being eliminated; Eurocodes can be applied only to new structures.
- ✓ Preventive strengthening of damaged structures with Carbon Fiber Reinforced Plastic Strips - CFRP and consequently, extension of remaining fatigue life can be taken in consideration. At present, in this direction, studies are performed.
- ✓ It is also important to mention that Annex C from Eurocode 3 “Choice of material to avoid brittle fracture” is based on fraction mechanics. The reliability of these method has been proved by calibration to a large scale of test results.

Example / Illustration / Case studies

The bridge in **Săvârşin** over the Mureş River on the local highway DJ 707 A was erected in 1897 , with four spans . The steel superstructure has a typical composition for the time period in which it was built, that is: steel deck, main parabolic truss girder with descending diagonals and posts, with trough deck slab laid on profiles of the Zorres type.

Figure 2: The Bridge in Savarsin

The technical condition of the bridge was unsatisfactory, the elements were corroded and some verticals and diagonals were damaged by the impact with the vehicles (Fig. 3, 4,).

Figure 3: Deformation defects

The existent floor beams, stringers and cross girders are simple supported elements. The deck consists on Zorres elements filled with ballast, supporting an asphalt surface. In present the structure has a special importance being the only crossing of the river in a large area. For the bridge in Sâvărşin in the first step, a classical simplified analysis was performed. The stresses computed in the structure for the present loads (Class E: continuous row of trucks with 30 tonnes **A 30** and a special military vehicle of 80 tonnes **V 80**) exceeded the allowable values by 10 – 40 %. Also the elements (posts) are very slender. The general stability of the compressed upper chord of the main girder was also checked.

Figure 4: Infrastructure defects

Taking into account the importance of the structure, its historical value the decision of strengthening of the structure was taken:

- ✓ for the stringers the flanges were consolidated by supplementary plates (Figure 5);
- ✓ the cross girders were transformed in switch girders (Figure 6);
- ✓ for the lower chord of the main girder a supplementary tie member was chosen (Figure 6);
- ✓ for the upper chord the direct strengthening with two angles, improving also the local stability was chosen (Figure 7);
- ✓ diagonals and vertical members have to be first of all straighten, and strengthen by additional plates (Figure 5);
- ✓ the old floor system was replaced by a composite deck. (Figure 8.)

All these operations are difficult and suppose a high technical level of all in situ works.

The decision for these rehabilitation works basis on the conclusions regarding the residual safety of the bridge.

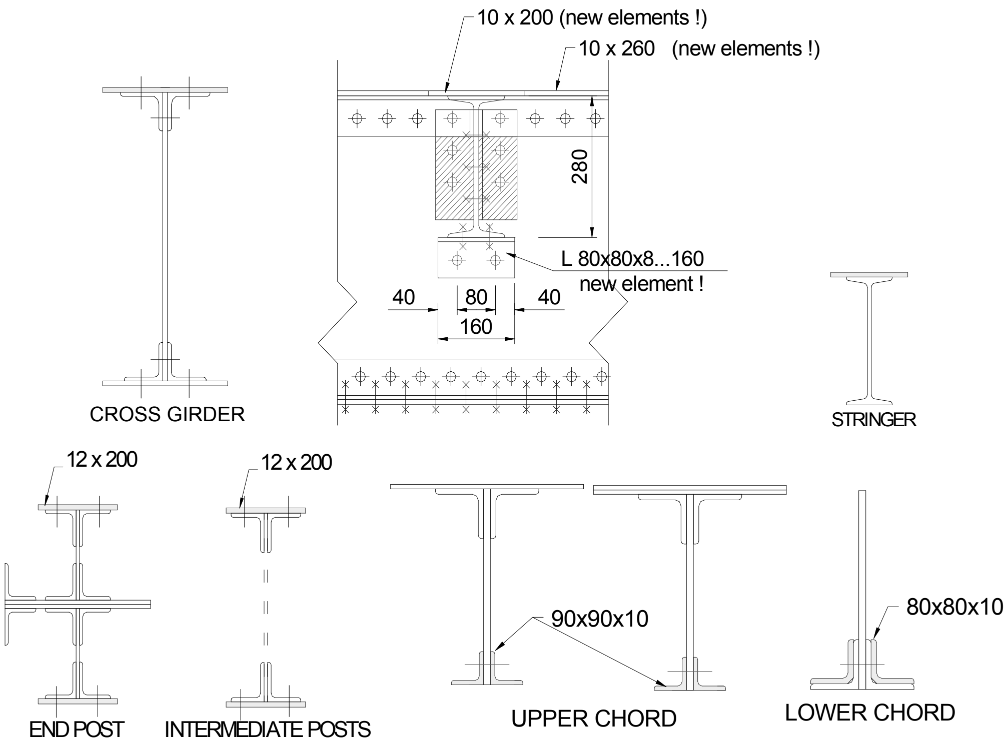

Figure 5: Direct reinforcement with additional elements

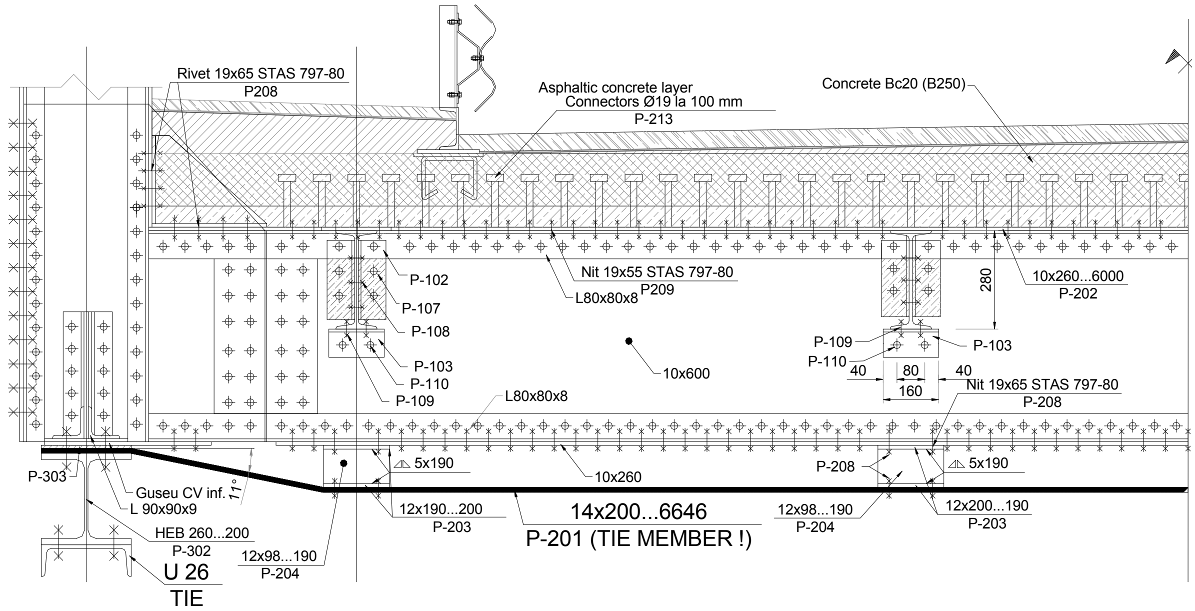

Figure 6: Strengthening of the structure (cross section)

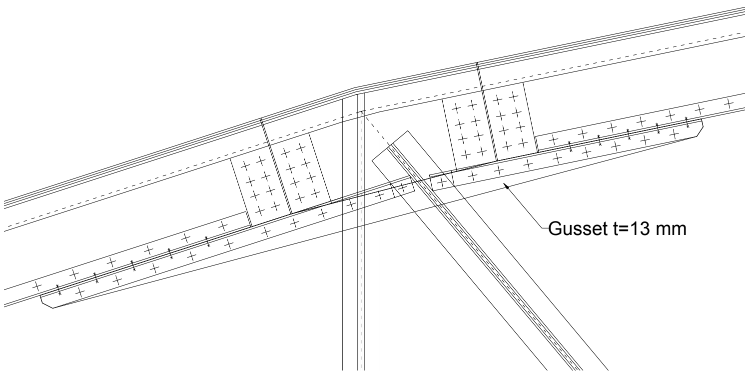

Figure 7: Upper chord strengthening

By taking into consideration all investigated cases it has been concluded that the fatigue in the case of this structure is satisfactory, meaning that it permitted strengthening.

For the assessment of the remaining service life it was practically impossible to perform an analysis based on the classical method of the damage accumulation hypothesis PLM. This can be explained by the fact that it is very difficult to recognize the stress history of the structure. Approximations made in the establishing of the past traffic lead to irrelevant results. Fatigue life calculations based on the classical method sometimes lead to the conclusion that there is no remaining service life, although there are no cracks observed in the structural elements.

That was the reason for which the complementary method based on fracture mechanics principles was chosen.

Assuming small detectable fatigue defects (cracks) emanating from the rivet holes and using the two steps fracture mechanics analysis one can determine the remaining fatigue life and the inspection intervals for this old riveted bridge.

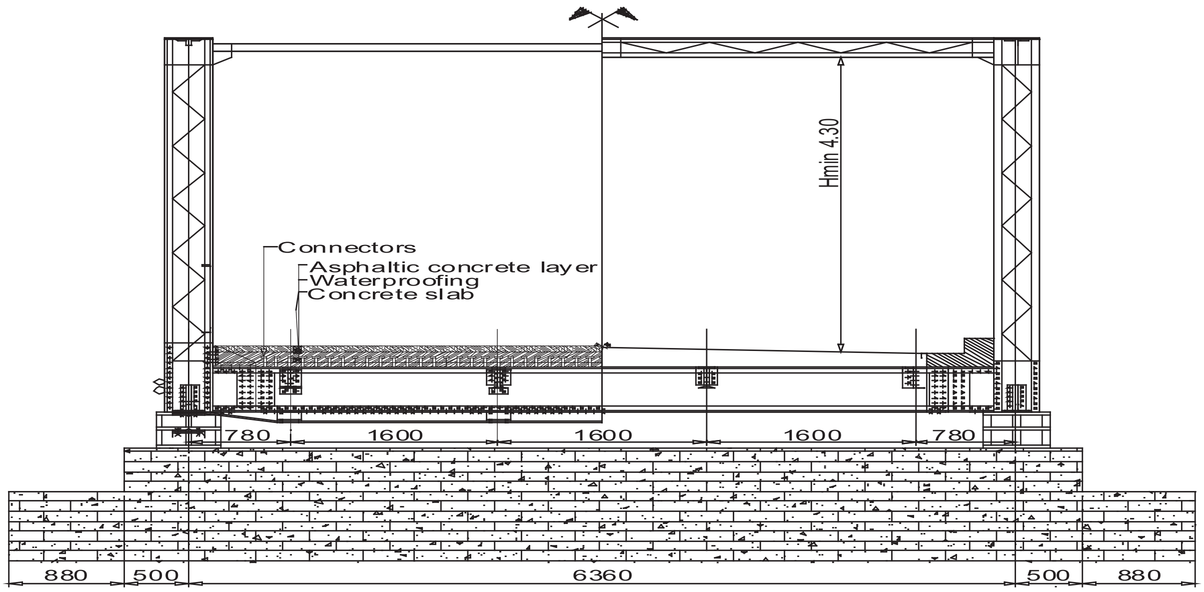

Figure 8: Cross section of the bridge

Finally after one and a half year the rehabilitated bridge was opened for the traffic.

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