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Experimental Stress Analysis

Improvement of Fatigue Life of Steel Orthotropic Desks with Carbon Fibre Reinforcement Composites

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Abstract: Orthotropic decks are progressive structural elements which often occur in civil and mechanical engineering. Besides the advantages like low weight, great stiffness, and low structural height, they suffer from dynamic forces causing fatigue cracks. Therefore it was tried to improve their fatigue properties and, thus, to prolong their life. The proof of gluing the Carbon Fibre Reinforcement Composites (CFRC) in the critical details of the deck seems to be encouraging. Strengthening of construction with use of external reinforcement materials manufactured from composite fibers is one of many ways to improve static and dynamic behaviour of structures.

Keywords: Orthotropic deck, Fatigue, Prolonged life, CFRC

1. Introduction

Steel structures with orthotropic decks have been built in several countries since the Second World War. Their number is very high, e.g. it was estimated more than 1000 on European Railway Bridges [15].

Being fully welded the orthotropic decks often show specific problems regarding the fatigue strength under dynamic loads. The most critical point on this type of structures appears in the neighbourhood of the area where the bridge deck joins the cross girder and longitudinal rib. The stress concentrations- a possible source of fatigue cracks- appear particularly in the web of the cross girder and/ or near the cutouts.

The results of fatigue tests of bridge elements reinforced with composites have provided a great dispersion. It is caused by not ideal similarity of elements, by not the same margin conditions, initial stresses etc.

The further difficulties appeared with the identification of cracks. We have applied three non-destructive methods (optic method with digital cover relation, active thermo graphic method and classic X-RAY radiographic method).

The idea to combine two various materials for achieving a better material is not new E.q., old Egyptians reinforced the bricks by straw and the fibres CFRC reinforced by polymers are one of the latest method which are now used as their characteristic such as modulus of elasticity (up to 600 GPa) and the strength in tension (up to 4000 MPa) are near to the corresponding characteristics of the strengthen material.

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2. Application of composite materials

The composite materials with external glued reinforcement are used to existing concrete, masonry, wooden and steel structures. The composite materials are applied to increasing the bending stiffness or to the reduction of shear cracks, etc. While the reinforcement of concrete and masonry has been well known, the reinforcement of steel structures is quite new.

Advantages of composite materials: low mass, high strength in tension, high fatigue characteristics, good anticorrosion properties.

Research on the use of CFRP materials for strengthening steel structures has been ongoing for approx. 15 years. However, comparably little in known about the environmental durability of the bond between CFRP materials and steel surfaces. See [1] for details.

3. Fatigue tests of steel flat bars

The investigations begun in with vests of steel bars and CFRC elements. In this way, we tested the steel flat bars for fatigue in tension as well as static tests with and without CFRC. The results can be seen in the Figs. 1. and 2. The dimensions and results test of bars without CFRC are in the Tables 1. and 2. at frequency 5 Hz.

Table 1. Flat bar specimens

specimen	F_{min}	F_{max}	Count of cycles	σ_{max} [MPa]	note
Sp 1	10	70	2 162 650	263	without fracture
Sp 2	10	85	802 855	317.6	
Sp 3	10	92	364 250	345.6	
Sp 4	10	97,5	430 040	368.3	
Sp 5	10	105	166 482	395.1	

Table 2. Flat bar specimens with CFRC

specimen	F_{min}	F_{max}	Count of cycles	σ_{max} [MPa]	note
Sp1-FRP	9.6	81.4	1 280 688	317.6*	Surface rough
Sp2-FRP	9.3	78.9	2 056 128	317.6*	smooth
Sp3-FRP	9.3	78.7	2 268 100	317.6*	smooth

*) The stress corresponded with the profile without CFRC ($A = 256{,}368\ mm^2$). The thickness of ht FRC with glue ~1.5 mm.

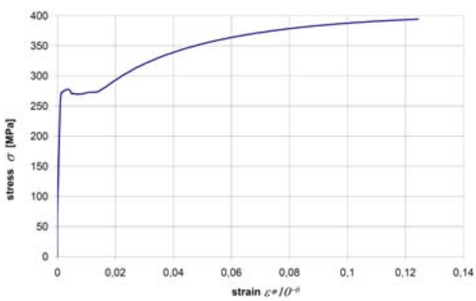

Fig. 1. The stress-strain diagram of a steel bar

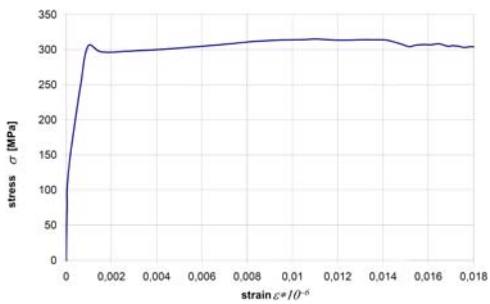

Fig. 2. The stress-strain diagram of a steel bar with CFRC

The dimensions of bars with CFRC are in the Fig. 3, steel 37, and surface is shown in the Tab. 2. The warp of fibrosis in the direction and perpendicular to the direction of tension stresses asymmetry of cycles: R = 0.1.

The load program in the bar sp1-CFRC was the same as applied to the specimen sp2, i.e. cyclic load in the range σ_{max} = 317.6 MPa. It was necessary to achieve the same stress as in previous tests. The fatigue life of a bar without CFRC was 802 855 cycles while the same one with CFRC was 1280688 cycles.

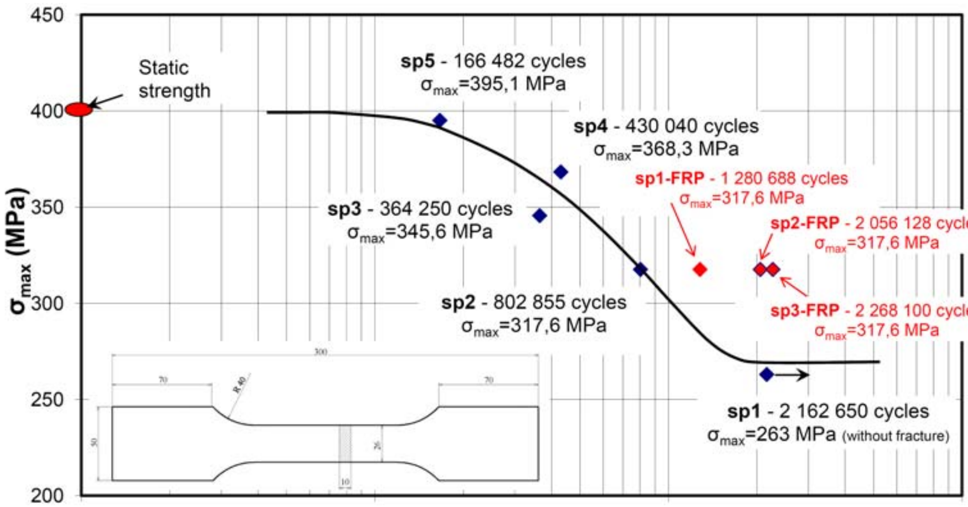

Fig. 3. Relation σ_{max} /count of cycles N

Fig. 3 is a function σ_{max} on the number N of cycles. The Wöhler curve belongs to the bar without CFRC. The specimen sp1-FRP was not polished while she other specimens were polished. The average static strength of not reinforced element is σ_{max} = 400 MPa at N = 10000 the left down diagram is a form of the specimen without CFRC.

The brushed surfaces of testing bars provided higher fatigue values. The importance of arrangement of surface before gluing is underlined in [6].

3.1. Glue and cloth test

We tested the glue SIKADUR-30 in simple tension of rectangular section 10 x 30 x 300 mm. We ascertained similar values as the producer temperature + 15 °C after 7 days hardening 24 to 27 N/mm^2. The Fig. 4. represents the relation F/(Δ*l*/*l*)of the Sikadur specimen.

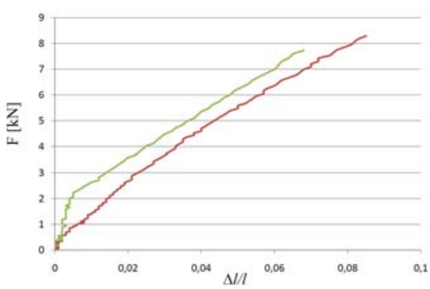

Fig. 4. Relation F/(Δ*l*/*l*) of the Sikadur specimen

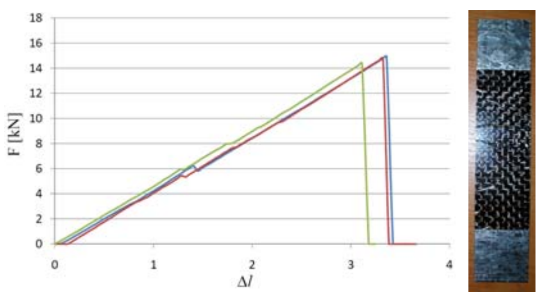

Fig. 5. Relation F/Δ*l* of the cloth

Reinforced cloth was tested in tension, Fig. 5. The values in tension and module of elasticity agreed with that one given by the producer. Further on, the strength of glue in shear is represented in the Fig. 6. The strength is 5.33 N/ mm^2 at the temperature 15°C after one day. It well corresponds of the producer data (F_{max} = 40 kN).

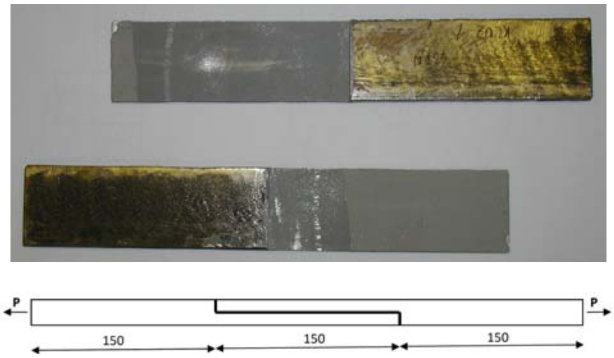

Fig. 6. The specimen for shear testing of Sikadur glue

4. Fatigue properties of specimens

Them the tests of specimens in the approximate scale 1 : 1 followed. Research of fatigue properties has been conducted in every advanced country. E.g. the International Union of Railways (UIC) and its European Rail Research Institute (ERRI) executed the research of orthotropic decks on railway bridges in the years 1990 - 1996, [8 to 14], and, now, the European Union has consecrated on this problem again in the research project BRIFAG (Bridge Fatigue Guidance - Research Fund for Coal and Steel of the European Commission granted under the contract Nr. RFSR_CT-2008-00033) [15].

The dimensions and forces of the specimens in the series ***A*** of the experimental programme mentioned above can be seen in Fig. 7. They have to correspond to the form and dimensions of real railway bridges as well as to the dimensions and force possibilities of the laboratory. The specimen in the Fig. 7 shows a part (slice) of the deck, cross beam, and longitudinal rib. On the railway bridges, the flat ribs are preferred for the closed ones because they not suffer by corrosion.

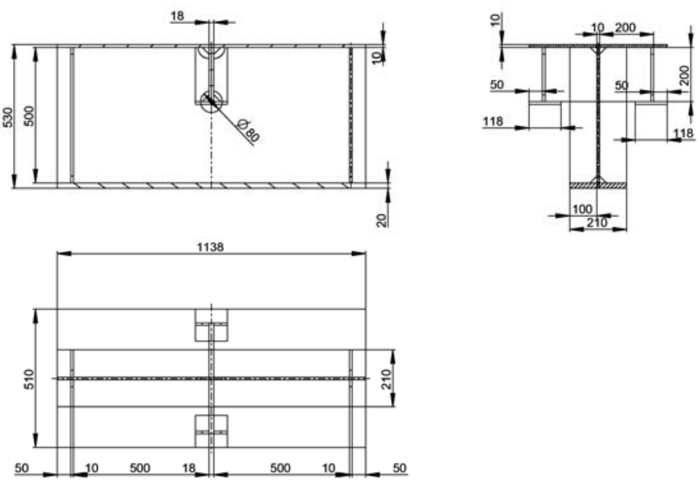

Fig. 7. The specimen series ***A***. The scale is 1:1

The fatigue tests of specimens 3 to 14 were carried out with respect to the Czech Standard. The test machine MTS with frequency 2 Hz was used, whereby the minimum and maximum forces, respectively, and the number *N* of absorbed cycles were recorded, see the Table 3.

Some of the fatigue cracks **m** can be seen in the Fig 8, while their propagation in the Fig. 9.

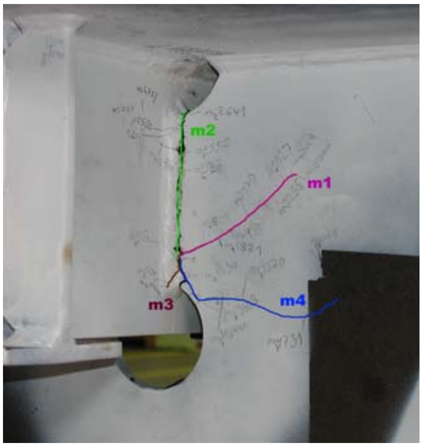

Fig. 8. Fatigue cracks **m** on the specimen 3.

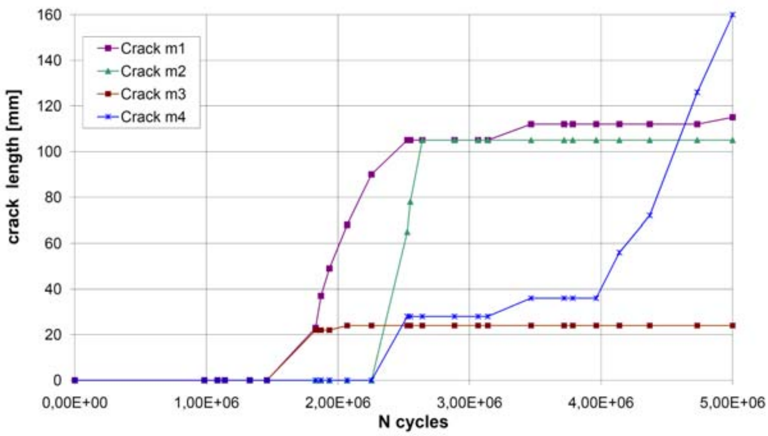

Fig. 9. Propagation of fatigue cracks on the specimen 3, i.e. crack length as a function of the number of stress cycles *N*.

Note : The number of cycles N indicates a state when the specimen is soft enough and deflection is higer than 10 mm.

A survey of tested specimens is shown in the Table 3 together with the most important results. The static maximum values are added for comparison; (specimen 1). The loading process provides a sinusoidal form with a minimum force F_{min} and maximum force F_{max}.

From Fig. 8 it may be estimated that the stress concentrations accompanying the cracks appear in the web of the cross girder and that one of longitudinal stiffener. Therefore, the plastic CFRC was glued in this critical area, Fig. 10.

The process of strengthening by the CFRC described above is valid in the following conditions: Gluing CFRC should be performed on the undamaged specimen. Gluing the CFRC after appearing the first fatigue cracks did not proof its worth. The problem in practice is that the uninformed inspection does not know where the cracks appear. It is a great disadvantage in practice. A survey of all results can be seen in Fig. 11.

Table 3. A survey of tests

N. of specimen	type of testing machines	F_{min} [kN]	F_{max} [kN]	Number of cycles N
1. static force	RK MFL PRUFSYSTEME	0	780	
2. dynamic force	MTS 250 kN, frequency 3 Hz	10	210	5 527 812
	GTM 500 kN, frequency 2 Hz	10	410	1 543 930
3. dynamic force	GTM 500 kN, frequency 2 Hz	10	360	5 000 000
4. dynamic force	GTM 500 kN, frequency 2 Hz	10	380	2 236 037
5. dynamic force	GTM 500 kN, frequency 2 Hz	10	390	547 400
6. dynamic force	GTM 500 kN, frequency 2 Hz	10	390	576 000
7. dynamic force (with CFRC)	GTM 500 kN, frequency 2 Hz	10	390	3 210 000
8. dynamic force (with CFRC)	GTM 500 kN, frequency 2 Hz	10	390	2 320 000
9. dynamic force	GTM 500 kN, frequency 2 Hz	10	390	596 453
10. dynamic force	GTM 500 kN, frequency 2 Hz	10	400	371 000
11. dynamic force	GTM 500 kN, frequency 2 Hz	10	400	716 000
12. dynamic force	GTM 500 kN, frequency 2 Hz	20	380	1 350 000
13. dynamic force	GTM 500 kN, frequency 2 Hz	20	400	820 000
14. dynamic force	GTM 500 kN, frequency 2 Hz	10	370	2 600 000

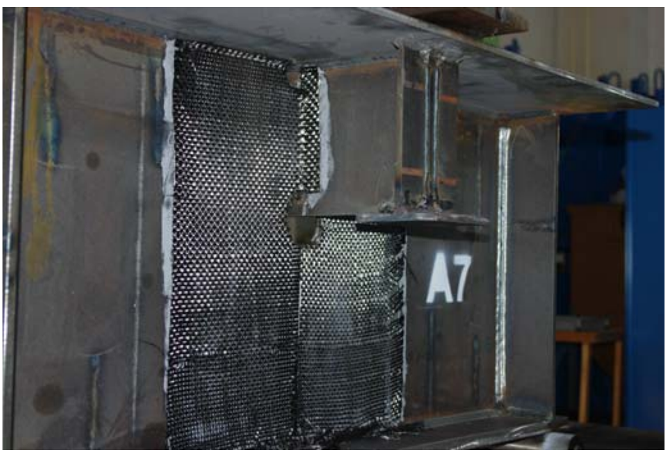

Fig. 10. The specimen 7 covered by the CFRC

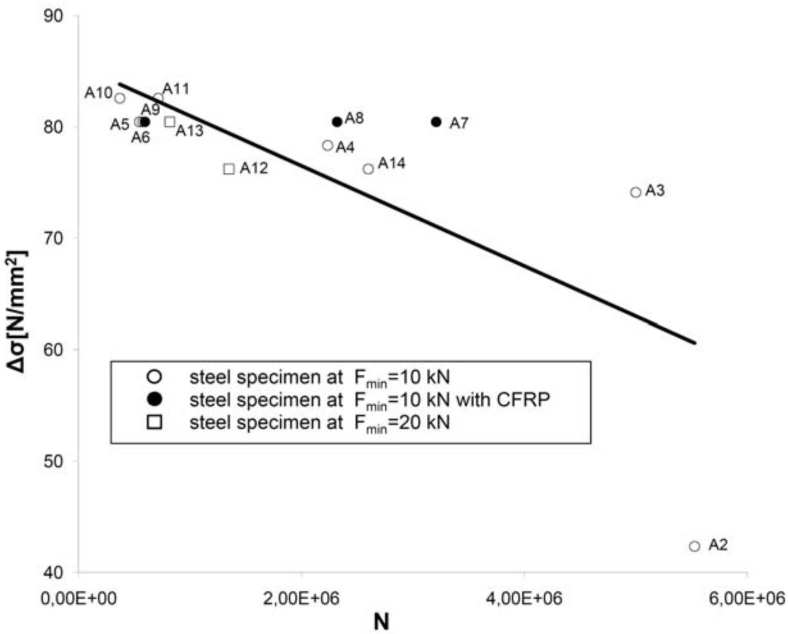

Fig. 11. Stress ranges $\Delta\sigma$ as a function of the number of absorbed cycles *N*. F_{max} see the Table 3

All the experimental results show increasing tendency of absorbed stress cycles when the specimens are covered with CFRC.

5. Conclusions

One possible process of improving the fatigue properties of orthotropic decks was suggested and tested. The fatigue life of specimens with CFRC is slightly increasing. Of course, the number of tests must be investigated in various laboratories, in different conditions as well as in miscellaneous circumstances including the improved quality of composites and glue.

The reasons of discrepancies lie in big differences of important mechanical properties (like modulus of elasticity, etc.) of the steel and plastic materials. Perhaps in future, they will be improved.

The present paper would like to stimulate the interest of researchers showing one possible method of improving the fatigue life of structures with following advantages: the method is non destructive, it does not interrupt the traffic with exception the time of gluing the CFRC and its hardening.

6. Conclusions

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