Statics and dynamics of orthotropic plates

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Abstract

Orthotropic plate has been investigated and the static and dynamic stresses were obtained using several theoretical and experimental methods: finite element method, folded plate theory, modal analysis, strain gauges, photoelasticity. An optimum form of cut-outs in the cross-girder is searched out and the paper presents several interesting conclusions about the stress distribution in the orthotropic plate.

1 Introduction

Orthotropic plates have been used as a bridge deck for both railway and highway steel bridges because they possess low structural hight and low weight. Therefore, a broad research of static, dynamic and fatigue properties of orthotropic deck is carried out for the European Rail Research Institute (ERRI), see [1].

The orthotropic bridge deck is composed of three main elements : plate, cross-girders and longitudinal ribs of open or closed cross-section. While the closed ribs are prefered for highway bridges, the open ribs are often applied to railway bridges. The present paper is concentrated on the last one. The cross-girders are equipped by cut-outs that enable their intersection with longitudinal ribs. The form of cut-outs has not yet been unified.

2 Static stresses

The static tests were carried out on a part of the orthotropic deck composed of one cross-girder with two ribs and plate. The approximate scale of this part was 1:1, the material : steel. Besides, the model of a complete railway

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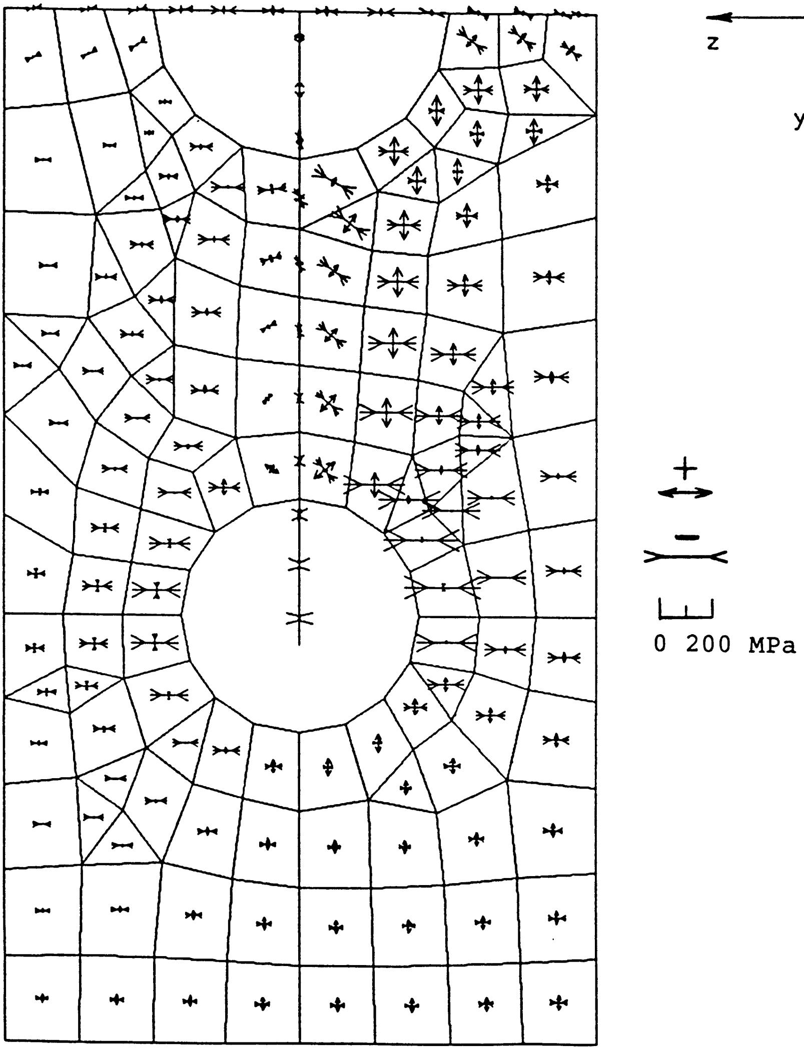

Figure 1: Main stresses σ_1 and σ_3 together with their angles in the cross girder.

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bridge in the scale 1:5 was produced from epoxide. The real span of the bridge is 15 m, while the model span 3 m.

The stresses in both cases were measured by strain gauges and observed in polarized light (photoelastic method). A thin layer of optically sensitive material was fixed to the surface of the steel elements of the orthotropic plate.

The finite element method and folded plate theory were applied to the calculations of stresses. While three forms of cut-outs were produced on the steel orthotropic plate, two forms on the epoxide model and six forms were investigated using the theoretical finite element model. In what follows only the results of the detail 1 with two round cut-outs are reproduced here.

The Figure 1 represents the distribution of main stresses together with their angles around the cut-out in the cross-girder (detail 1). The programme ANSYS was used for the calculation, [2]. The form and size of finite elements can be also seen in Figure 1.

The strength of materials is characterized according to the Huber-Mises-Henke theory by the equivalent stress

$$\sigma_{eq} = \{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]\}^{\frac{1}{2}} \tag{1}$$

where σ_1, σ_2 and σ_3 denote the main stresses.

The equivalent stress was calculated for the same case as in Figure 1 and its distribution in the cross-girder is reproduced in Figure 2.

It was observed that the equivalent stress crosses the elastic limit of the steel at some points. Therefore, the calculations were repeated for the same case and the ideal elastic-plastic behaviour of the material was taken into account. The results of this calculations are shown in the Figure 3. The corresponding stress-strain diagram is in the Figure 4 and the iterative procedure was applied to this non-linear case.

The residual stresses after welding are very important for the fatigue of orthotropic plates. A special non-destructive method [3] gives the distribution of residual stresses in the steel orthotropic plate. Their values are rather important and they may reach dozens of Megapascals.

3 Dynamic tests

The dynamic response of the epoxide model of a railway bridge was obtained by an electrodynamic exciter and its response was measured by the acceleration indicators in the network with 55 points. The exciting frequencies varied from 5 to 150 Hz.

The modal analysis after orthogonalizing provided six natural frequencies and corresponding modes of natural vibration. The first three of them are demonstrated in the Figure 5.

The first natural frequency of the unloaded bridge model is

$$f_1 = 24,19 Hz, \tag{2}$$

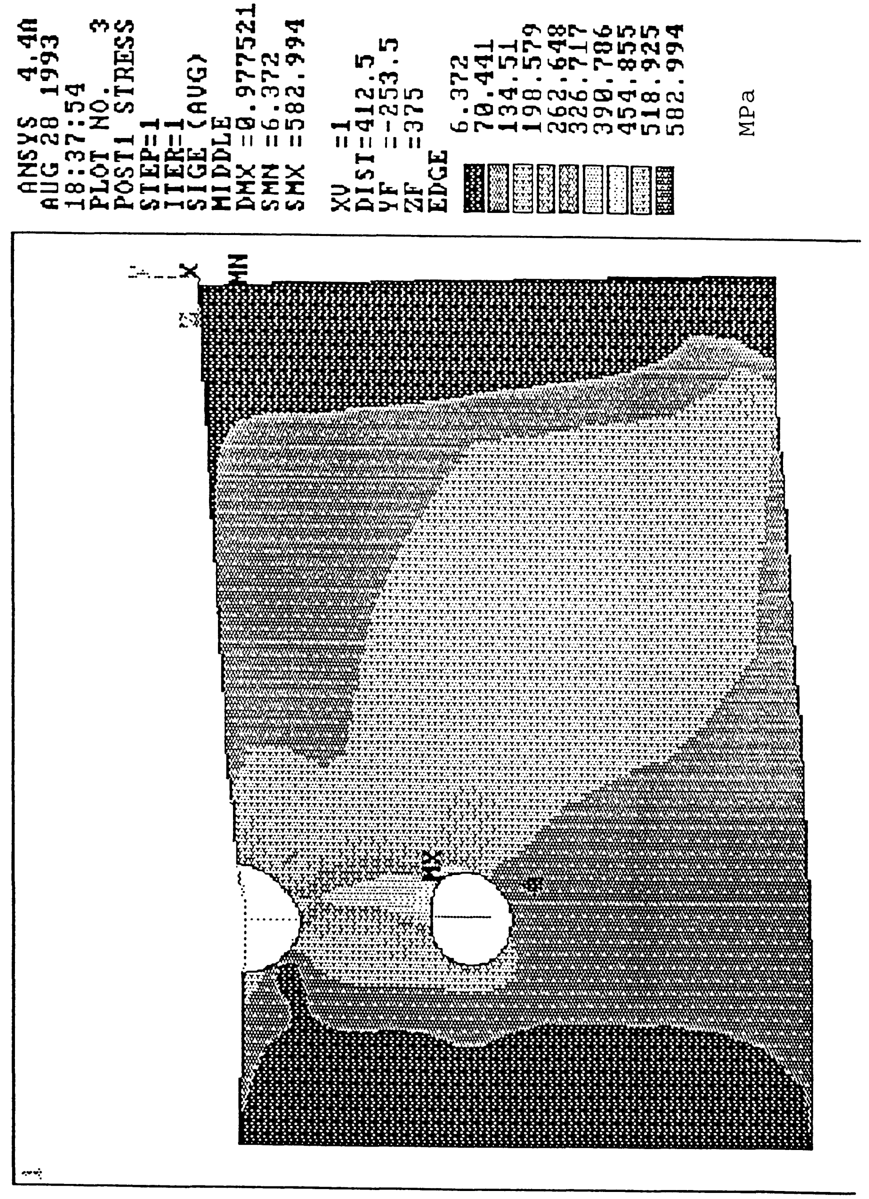


Figure 2: Distribution of equivalent stress σ_{eq} in the crossgirder, elastic analysis.

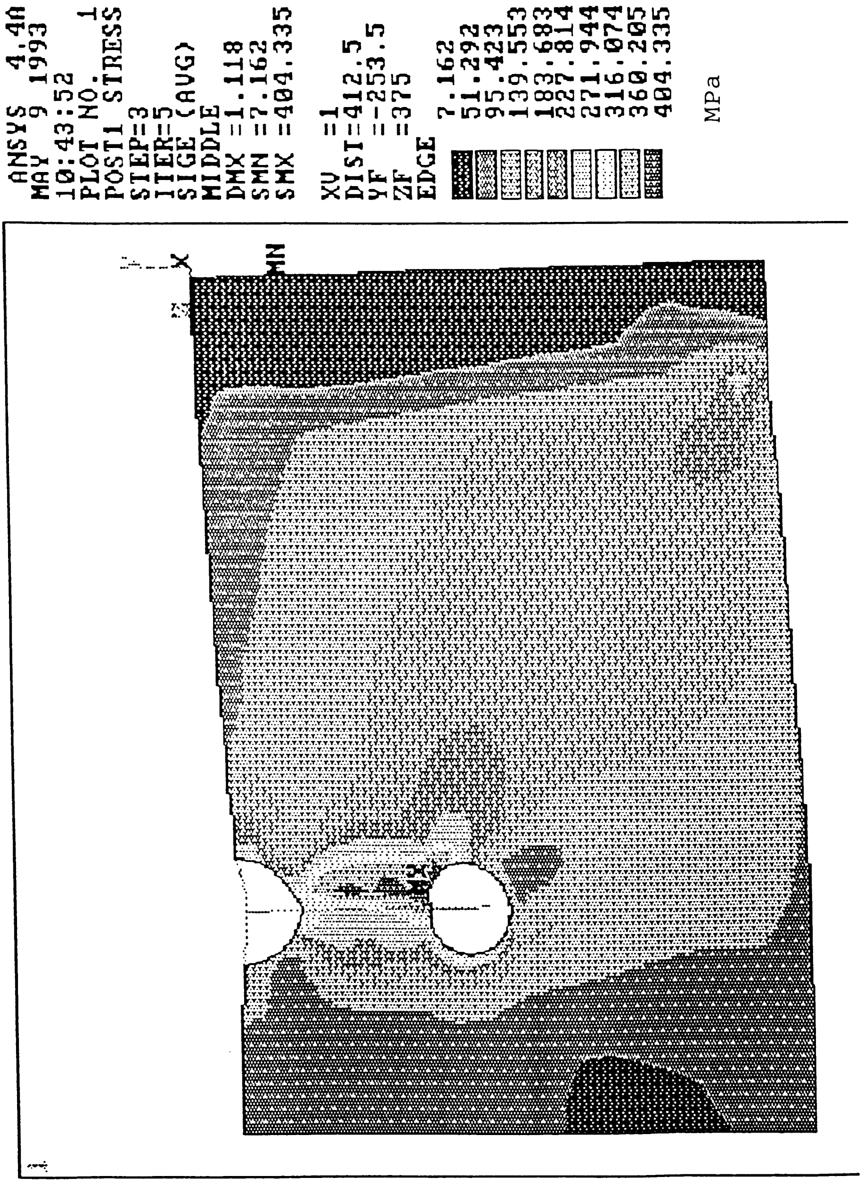


Figure 3: Distribution of equivalent stress σ_{eq} in the crossgirder, elastic-plastic analysis.

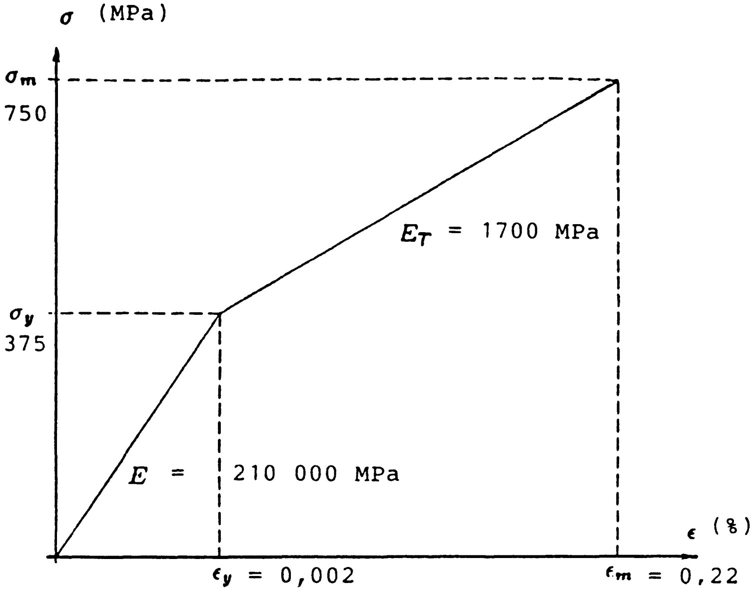


Figure 4: Ideal elastic-plastic stress-strain diagram.

see Figure 5, while the elementary calculation (bridge = simple beam, [4]) gives

$$f_1 = [\frac{\pi}{2l^2}](\frac{EI}{\mu})^{\frac{1}{2}} \tag{3}$$

with the following data :

$l = 3000mm$ - span of the bridge model,

$E = 4200MPa$ - modul of elasticity of epoxide,

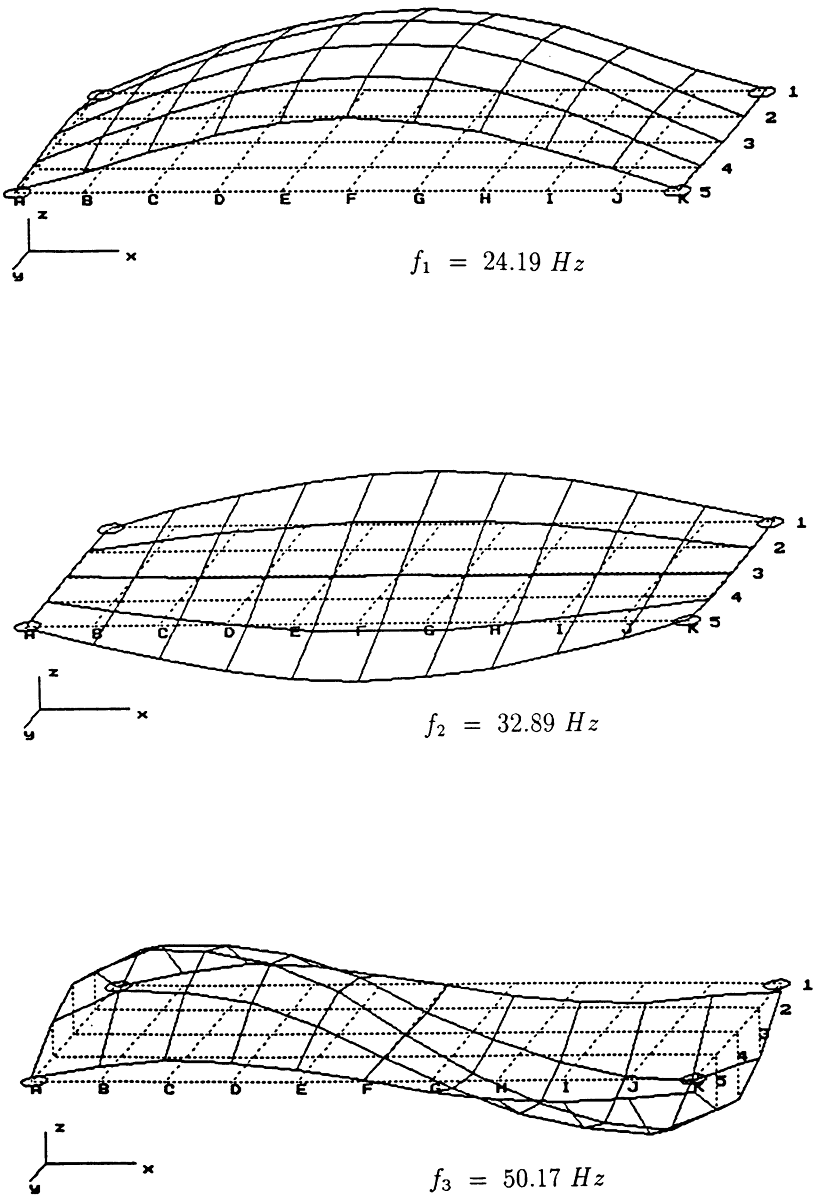
$I = 7,155.10^7mm^4$ - moment of inertia of the bridge cross-section including plate and ribs,

$\mu = 1,709.10^{-5}Ns^2/mm^2$ - mass per unit length of the bridge model.

The second natural vibration mode with $f_2 = 32,89Hz$ corresponds to the torsion of the bridge, see Figure 5.

4 Fatigue tests

The dynamic tests on fatigue were carried out by the Railway Research Institute in Prague and by the Institute of Metal Structures of the University in Lausanne. They have shown the importance of the quality of welding and of penetration. Due to big stress concentrations in the orthotropic plates



$f_1 = 24.19\ Hz$

$f_2 = 32.89\ Hz$

$f_3 = 50.17\ Hz$

Figure 5: First three natural frequencies and modes of natural vibration of the bridge model with orthotropic deck.

the measured fatigue limits lie in the lower area of normalized Wöhler lines (according to the classification in the Eurocode 3).

5 Conclusions

The deflection and stresses in the main girder of a bridge with orthotropic deck may be found using an elementary theory. Even the correspondance between the experiment and elementary theory for the calculation of the first natural frequency is satisfactory.

However, the stresses near the spatial intersection of the plate, cross-girder and longitudinal rib should be calculated using a more advanced theory like finite element method.

It has appeared that the stress concentrations occur near to the spatial crossing of the plate, cross-girder and rib and they are affected by the size and shape of the cut-out in the cross-girder. Both theory and experiments show that the bigger the cut-outs the greater stress concentrations occur.

The residual stresses have provided an opposite conclusion : the longer the weld seams the greater residual stresses. Therefore, an optimum has to be found between cut-outs and weld seams.

It has appeared that the stresses at some points may be higher than the elastic limit of applied steel. The elastic-plastic behaviour of the orthotropic plate causes a redistribution of stresses : the stress peaks from the elastic analysis are cut off after plastification but the area with high stresses is extended.

The fatigue tests have shown the importance of the quality of welding and of penetration. The fatigue cracks are going from the stress concentrators and/or from weld seams or penetration.

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