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Verification of details of existing structures with the elastic-plastic stress field method

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Abstract

The verification of critical details of existing structures is generally performed with strut-and-tie models. An alternative widely used in some countries, such as Switzerland or Denmark, is the rigid-plastic stress fields (RPSF) method (based on the lower bound theorem of plasticity) which allows for the consistent and systematic analysis of a variety of structural elements and details. It however requires a certain level of experience to be applied to a wider range of cases and in order to consider the various load-carrying actions. Therefore, the verification of existing structures requires a more systematic method. The elastic-plastic stress field method (EPSF) was developed at EPFL in order to overcome the limitations of the rigid-plastic stress field method. It takes into account the resistance of the concrete as a function of the deformations and has proven to give good estimates of the strength of reinforced concrete members.

In the framework of this project it is intended to study the applicability of the EPSF and the RPSF for the assessment of certain complicated details specific for concrete bridges. In order to do that, a large amount of performed tests available in the literature will be analysed with the two methods. Some of the details that are studied are zones of introduction of concentrated forces, cantilevers with dapped ends, diaphragms, and the extreme ends of beams with poor anchorage of the reinforcement which can simulate the behaviour of prefabricated beams. The results will then be used to develop guide-lines for the choice of the coefficient accounting for the reduction of the compressive strength of the concrete due to transversal strains and the angle of the inclination of the compressive struts.

Keywords

Structural analysis and design; Existing structures; Reinforced concrete bridges; Critical details; Stress fields; Strut-and-tie modelling; Support zone; Dapped beams;

1 Introduction

Critical details in bridges can be regarded as the potentially weakest members of a structure, thus governing its strength. This is typically the case of geometrical discontinuity of the cross section or the reinforcement provided or the action of concentrated loads (fig 1). In order to better understand the behaviour of such regions a large number of tests have been performed over the decades and simple strut-and-tie models have been proposed by many researchers. More refined analysis of the discontinuity regions can be performed with RPSF accounting for the actual reinforcement layout. However, the concrete strength is still modelled based on rules. The EPSF allows for the detailed modelling of both the reinforcement and the concrete, and is a promising tool for such analysis.

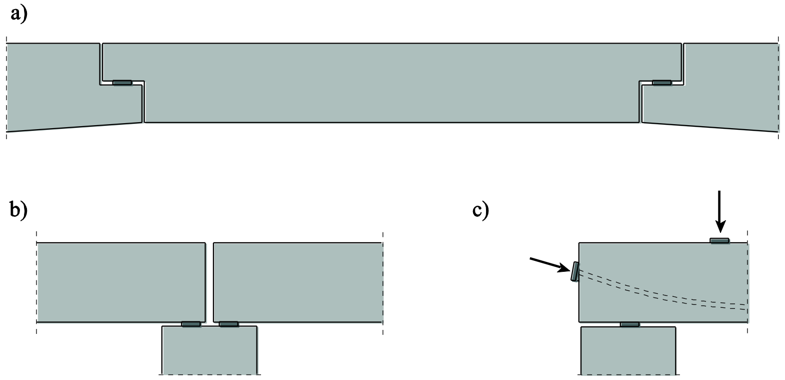

Fig. 1 Discontinuity regions typical for concrete bridges a) dapped end b) insufficient anchorage c) concentrated forces due to prestressing and traffic

It is the goal of this research, by using the EPSF method, to develop RPSF models to be solved by hand of common for concrete bridges details, to verify the applicability of the EPSF method for these details and to provide guidance for the development of more accurate strut-and-tie and RPSF models.

2 Numerical modelling with EPSF method

The Elastic Plastic Stress Field (EPSF) method was developed at EPFL, Switzerland and was implemented in a computer program [1], [2]. The access for students at EPFL and practicing engineers is free (http://i-concrete.epfl.ch) and the source code of the program can also be downloaded. This program provides an accurate and quick solution for 2D engineering static problems and for the analysis only two parameters are required - the strength and the modulus of elasticity of the materials. The main assumptions of the elastic-plastic stress field method (EPSF)(fig. 2) are:

- Mohr-Coulomb yield surface for plane stress with tension cut-off
- elastic perfectly plastic behaviour of concrete in compression
- perfect bond between concrete and reinforcement

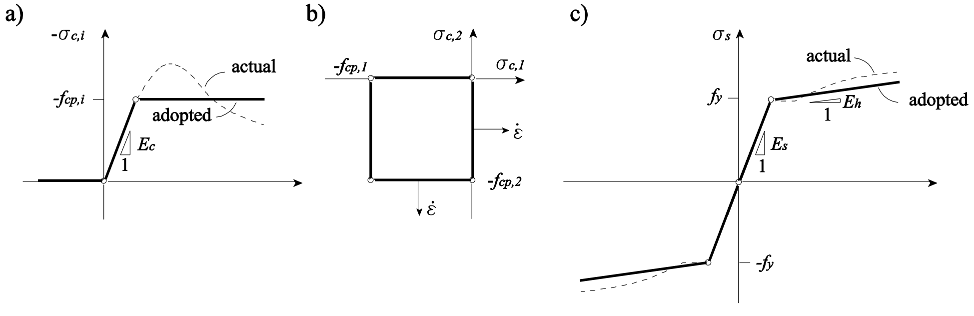

Fig. 2 a) constitutive model for the concrete b) Mohr-Coulomb yield surface c) constitutive model for the steel

To account for the brittleness of the concrete (fig 2a) the effective plastic concrete strength in compression is calculated as:

$$f_{cp} = f_c \cdot \eta_{fc} \tag{1}$$

with the coefficient ηfc, as introduced by Muttoni [3] :

$$\eta_{fc} = \left(\frac{30}{f_{ck}}\right)^{1/3} \leq 1 \tag{2}$$

The effect of the transversal strains ε_1 on the compressive struts in the concrete is accounted for with the coefficient k_c, as introduced by Vechio and Collins [4]:

$$k_c = \frac{1}{0.8 + 170 \cdot \varepsilon_1} \leq 1 \tag{3}$$

For the steel a bilinear constitutive law is introduced in the program with the possibility to account for strain-hardening.

3 Applicability of the EPSF method

In order to validate the applicability of the EPSF method a wide range of test specimens were selected. In the following paragraphs some of the selected test programs are discussed and the results obtained with the program *jconc*, based on the EPSF method are presented in Table 1.

Kuchma performed a total of 20 tests on high-strength prestressed bulb-tee girders [5]. The results from specimens G10E and G10W (which were strengthened with FRP sheets) and specimen 8E (in which an interface in the concrete was done by steel plates) are not discussed in the statistics because at present they are out of the scope of the program *jconc*.

Kaufmann and Ramirez performed tests on a total of 3 AASHTO Type II and 6 Type I prestressed girders [6]. The goal of the test program was to validate the current provisions for the use of high-strength concrete. The specimens failed due to insufficient anchorage, shear and bending.

Leonhardt and Walther tested a total of 15 T-beams with high amount of shear reinforcement and the anchorage length of the longitudinal reinforcement beyond the support was varied [7]. The results from specimens TA7 and TA8 are not included in the statistics because almost no longitudinal reinforcement was provided at the support.

Sagaseta and Vollum tested a total of 14 rectangular beams [8] (four of the beams were without shear reinforcement and they are not included in the final statistics). The main parameters varied in the test were the aggregate size and the loading arrangement. The goal of the experimental program was to investigate the effect of the compression zone and to compare the results with similar tests on T- and I-sections.

Table 1 Statistical analysis of the results from the analysis of specimens from literature with EPSF

Selection		
Bulb-Tee Girders	# specimens included	17
	Average	1.08
	COV, %	4.75
AASHATO Type I and II Girders	# specimens included	9
	Average	1.09
	COV, %	9.96
T-beams	# specimens included	13
	Average	1.10
	COV, %	6.58
Rectangular beams	# specimens included	10
	Average	1.04
	COV, %	7.97

For the assessment of the applicability of the EPSF method, the ultimate strength of the element was not the only parameter investigated. Additionally, a detailed analysis of the distribution of the angle of the compression struts θ and the coefficient k_c (Eq.3) is performed, as well as comparison with observed failure modes and measurements. The results of a test specimen from the test campaign [5] obtained with the program based on the EPSF method are presented in Figure 3.

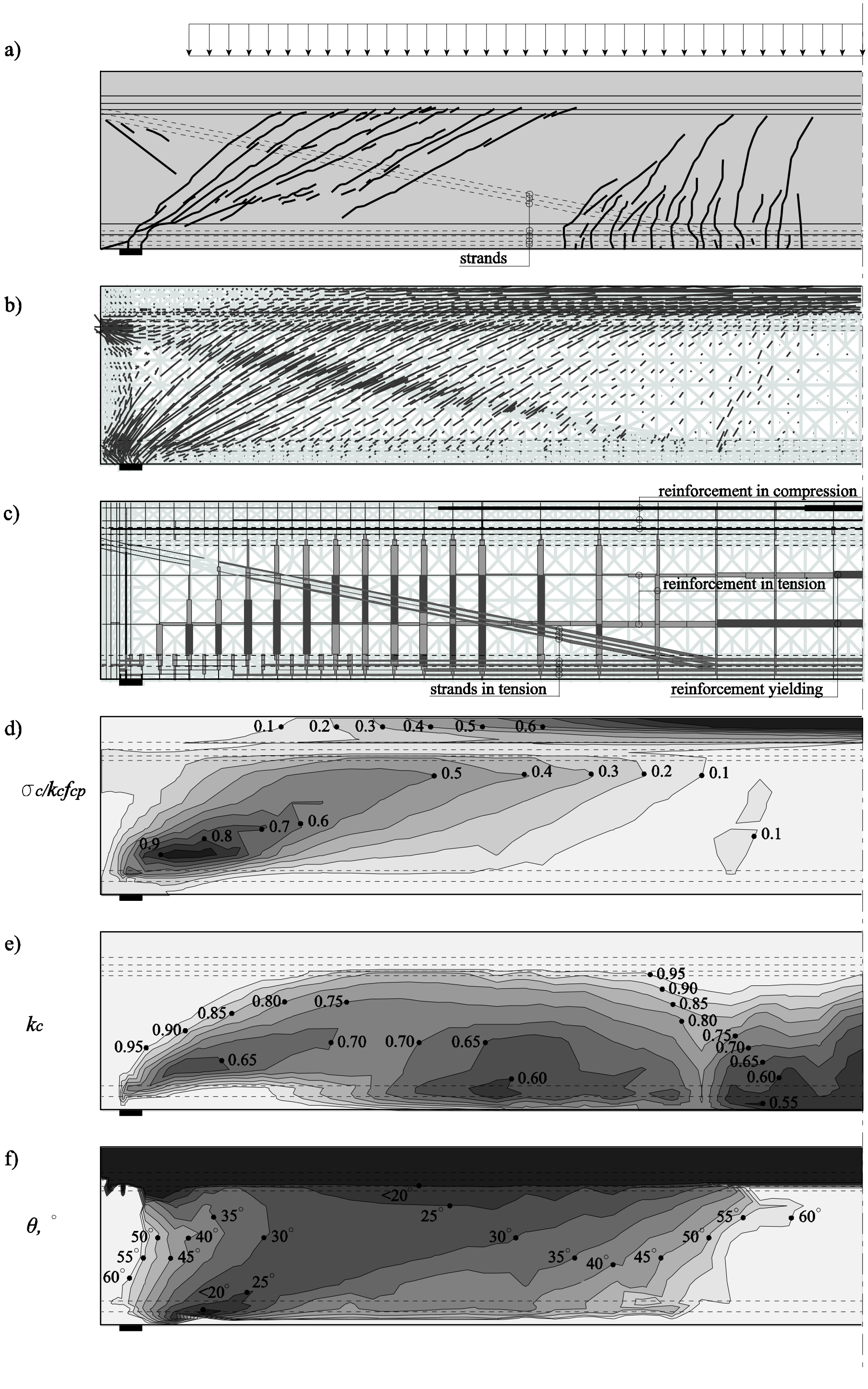

Fig. 3 Girder 1 East End, [3] a) cracking pattern and loads; b) direction of principal compressive stresses c) stresses in the reinforcement and the strands d) degree of use of concrete strength e) distribution of the coefficient k_c f) angle of principle compressive stresses in the concrete

4 Development of RPSF models

In order to present the development of the RPSF models an example of a specimen tested by Rainer and Elbadry [9] will be discussed. In this experimental program a total of seven dapped end specimens with inclined and straight shear reinforcement were tested. The ultimate load bearing capacity of all specimens was calculated with a strut-and-tie model and the average ultimate load predicted was approximately 70% of the actual one. The reinforcement layout and the strut-and-tie model used for the analysis of specimen A are presented in Figure 4.

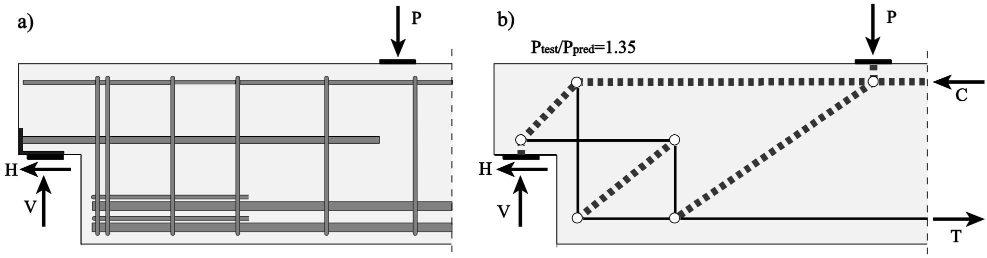

Fig. 4 Dapped End A a) reinforcement layout; b) strut-and-tie model used for the analysis

The specimen A was analysed with the program *jconc* and the results are presented in Figure 5a. It can be observed that the load transfer path obtained with the program differs from the one originally proposed in [9]. The additional concrete strut can be accounted for only if the detailed reinforcement layout is considered. The presence of this additional load-transfer action can be observed also in the crack pattern of the specimen.

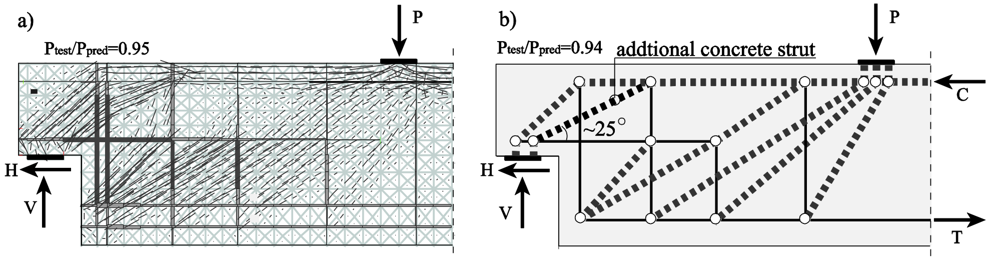

Fig. 5 Dapped End A a) model in *jconc*; b) refined strut-and tie model

Based on the refined strut-and-tie model (fig.5b) a RPSF model was developed (fig.7b), where a coefficient of k_c equal to 0.6 as usually adopted for such design was taken. The presence of wide crack openings in the region between the nib and the beam was observed during the test. From the analysis of the distribution of the coefficient k_c with *jconc* (Figure 6a), it can be concluded that the program can accurately predict the large transversal strains in this region which lead to wider crack openings (k_c=0.3).

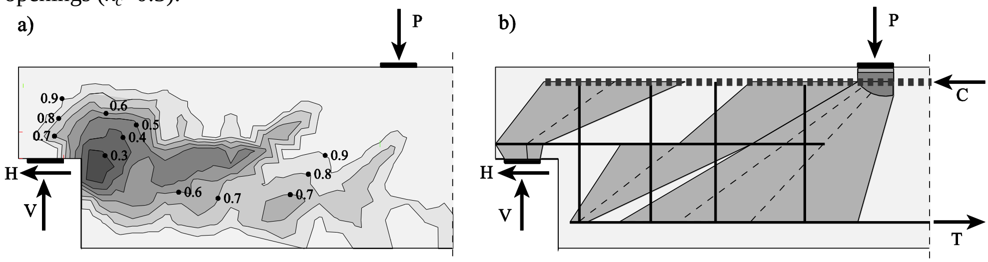

Fig. 6 Dapped End A a) distribution of the coefficient k_c; b) RPSF model

5 Conclusion

From the analysis of the results it was concluded that for certain critical details (such as insufficient anchorage of prestressed girders with sufficient shear reinforcement) the EPSF can accurately predict not only the load bearing capacity but also the mode of failure. Additionally, the computer program *jconc*, based on the EPSF method, is a valuable tool which allows for the development of rigid- plastic stress field models for common details.

Future work consists of analysis of a wider range of typical for reinforced concrete bridges details and investigation of different parameters such as concrete strength, reinforcement ratio and layout, type of loads, etc.

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