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Bending, shear and patch loading interaction behaviour of slender steel sections

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Abstract

The new Hárosi Danube bridge on the M0 highway around Budapest has been designed and erected between 2010-2012. The superstructure of the bridge is a continuous steel box girder with 3 spans (3 x 108.5 m). The independent static check in the final stage and during the launching phases are made by the BME Department of Structural Engineering. The current paper focuses on the numerical modelling technique and on the specialities of the static check of this bridge structure during launching. An additional research program is also related to the static check of this bridge structure, which was made in cooperation with the University of Stuttgart and the Universitat Politècnica de Catalunya. During launching nearly all cross-sections come at least once over a support where a concentrated reaction force, large bending moment and shear forces are introduced and hereby buckling problems may arise in the slender web panel. In the current version of EN1993-1-5 [1] there is no standard design method to take the interaction of these three effects into account. Therefore our research work focuses on the interaction behaviour of longitudinally unstiffened and stiffened steel girders under the combination of bending, shear and patch loading.

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Keywords: bridge launching; interaction; bending; shear, patch loading; stiffened plated structure.

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1. Introduction and problem statement

A new highway bridge over the Danube has been built in Hungary on the south part of the M0 highway around Budapest between 2010 - 2012. The superstructure of the bridge is a box section girder having longitudinally stiffened webs and flanges with relative large slenderness. The erection method of the bridge was incremental launching. This erection method is nowadays likely used in Hungary due to its numerous advantages considering its time and cost

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efficiency. This building process, however, involves a problem with buckling of the thin steel web under combined bending, shear and transverse force. During launching nearly all cross-sections come at least once over a support where a concentrated reaction force, large bending moment and shear forces are introduced and hereby buckling problems may arise in the slender web panel. Bearing stiffeners give no solutions in case of moving loads, therefore it is necessary to determine the resistance of the web panels under the combined loading situation. In the current version of the EN1993-1-5 [1] the calculation methods of the bending, shear buckling and patch loading resistances are given. Interaction equations are also included in the standard for bending and patch loading (M-F) and bending and shear buckling (M-V) interactions. On the other hand previous studies have been executed in the field of bending and transverse force (M-F) and shear and transverse force (V-F) interaction by Braun and Kuhlmann [2]. But there is no design interaction equation for the M-V-F interaction behaviour, and there is a very small number of previous investigations in the international literature dealing with the combined loading situation of all these three effects. The only investigations in this field were made by Braun and Kuhlmann [2] in 2010 and Graciano and Ayestarán in 2013 [3]. The original aim of Braun and Kuhlmann was the investigation of the bending and patch loading interaction (M-F) and the shear and patch loading interaction (V-F) separately. Based on the results in the M-F and V-F interaction behaviours a combined M-V-F interaction equation was proposed to consider the combined loading situation. The BME Department of Structural Engineering made the static check of the new Hárosi Danube bridge and executed all the necessary static calculations for the bridge launching phases. However the static check of the largest cantilever stage could be not performed by analytical design methods according to the EN1993-1-5 and it was investigated by an advanced FE model and the static check for the combined loading situation was made by GMNI simulations.

The current research program had therefore two aims. The first aim was to execute the static check of the bridge structure during the erection phases for the M-V-F loading situation using FEM based design method. Parallel to the practical application of our results the authors started a common research activity with the University of Stuttgart and the Universitat Politècnica de Catalunya to investigate the M-V-F interaction behaviour of longitudinally stiffened and unstiffened girders. The research aim was an in-depth investigation of the applicability of the previously proposed M-V-F interaction equation in a large parameter range for various internal force distributions with various girder geometries. Based on the current numerical investigations the M-V-F interaction equation developed by Braun and Kuhlmann [2] has been verified. The numerical calculations proved its applicability in an extended parameter range what was previously not analysed. Based on the current research results the design according to EN1993-1-5 [1] will be possible for the M-V-F interaction what is not negligible for the static calculations in case of bridge launching.

2. Numerical modelling of the launching process and design of the superstructure

The superstructure of the bridge is a 3 span continuous box section girder with a total length of 3 x 108.5 m = 325.5 m. The cross section of the bridge consists of longitudinally stiffened flange and web plates. The width of the carriageway is 18.0 m with a sidewalk of 1.9 m width on both sides. The depth of the box section is 4950 mm. The distance between the web plates at the bridge deck is 11700 mm, while at the lower flange this distance is equal by 9000 mm. The thickness of the web plates are 12 mm along the main part of the bridge, which are increased up to 20 mm at the internal support regions. The bridge deck is an orthotropic plate having 14 mm thickness and closed section longitudinal stiffeners at each 600 mm. The bridge deck is supported by cross girders located at each 3875 mm, with a web depth of 1000 mm. Longitudinal stiffeners are manufactured from steel plates having 8 mm thickness The thickness of the lower flange is 10 mm on the main part of the bridge along its longitudinal axis, which increases up to 30 mm in the support regions. The web and lower flange plates are supported by longitudinal stiffeners having trapezoidal cross sections with 200 mm web depth and 8 mm plate thickness. The box section is stiffened at all the second cross girders by a truss diaphragm. The typical cross section is presented in Fig. 1. The bridge was designed by the Hungarian designer office PontTerv Zrt. and it was erected by the Közgép Zrt. To perform the independent static check a detailed numerical model was developed by the BME Department of Structural Engineering using Ansys 14.5 [4] finite element software. The applied numerical model is a full shell model containing all the plates which can be found on the shop-drawings (all the stiffeners, ribs, diafragms). A detailed FE model is developed to be able to analyse the deformations and stress distributions under the launching process. To investigate the whole launching process step-by-step (325.5 m launching length) in a 2 meter sequence an automatic calculation and evaluation process is developed. In this calculation process the differences between the erected bridge geometry and the launching path is also considered, and for all the launching phases the static check of the complete bridge girder is executed.

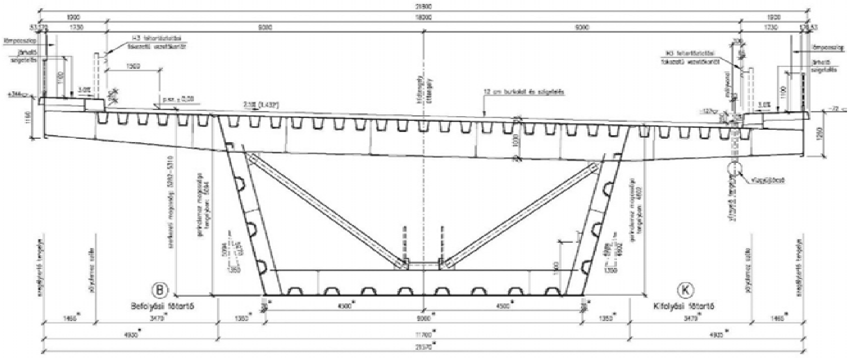

Fig. 1. Typical cross section of the bridge.

The highest utilization ratio is observed in the longest cantilever stage before the launching truss reaches the pier, as shown in Fig. 2. In this launching phase a very high negative bending moment is acting in the cross section of the previous pier with an accompanying large reaction force and a moderated shear force. However the application of the launching pylon could increase the shear force level as well in several launching stages.

Fig. 2. Launching process of the Hárosi Danube bridge and position with the larges utilisation ratio.

Thus there are no standard design method available to make the detailed static check of this loading situation, the M-V-F interaction is checked by using the FE model (Fig 3.a) and by application of FEM based design method. To calculate the ultimate load of the bridge structure GMNI simulation is executed (geometric and material nonlinear analysis using equivalent geometric imperfections). The typical failure mode and the ultimate shape in the largest cantilever stage can be seen in Fig. 3b.

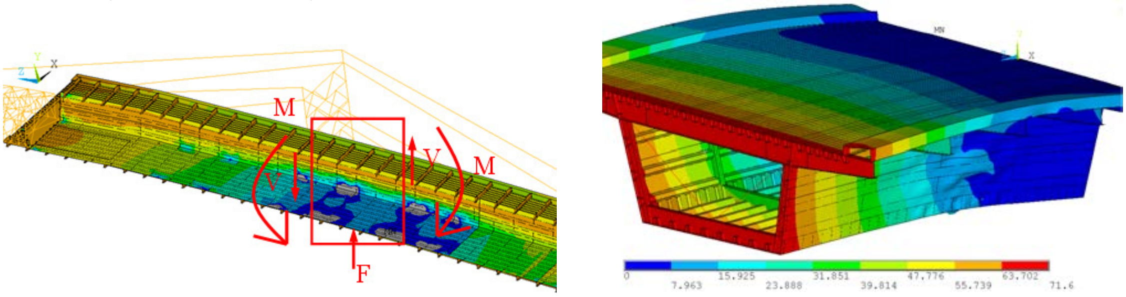

Fig. 3. FEM based design using GMNIA simulation: a, loading situation b, failure mode under M-V-F interaction.

The final results of the numerical simulation is the failure mode and the typical load – displacement curve of the analysed girder, as shown in Fig. 4. The horizontal axis of the diagram shows the calculated displacement and the vertical axis represents the load amplifier related to the combined loading situation. The red curve represents the vertical deflection of the cross section and the blue curve shows the lateral displacement of the points having the largest displacement in the web. The characteristic and design resistance levels and the design load level are presented on the diagram with horizontal lines, which values are the bases of the static check. The relative large difference between the characteristic and design resistance levels are caused by the fact, that all the static calculations had to be performed on the safety level of the Hungarian standard [5].

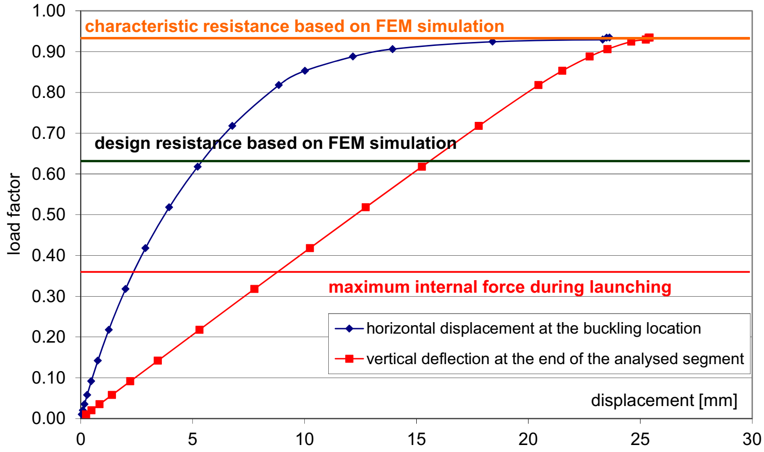

Fig. 4. Load-displacement curve representing the structural behaviour and ultimate resistance.

The FEM based static calculation could be made relatively fast in this particular case and the launching process could be verified, however the calculation difficulties draw our attention on the need of a hand calculation method development to be able to check the M-V-F interaction behavior without using FEM based design. Therefore an accompanying research project has been stated at the BME Department of Structural Engineering in cooperation with the University of Stuttgart and the Universitat Politècnica de Catalunya.

3. Research program on M-V-F interaction behaviour

To investigate the M-V-F interaction behaviour of the slender steel structures the existing experimental, analytical and numerical investigations are analysed, evaluated and compared. To extend the previous investigations and to analyse the applicability of the previous design proposals a numerical model is developed. Based on the model the bending, shear and patch loading resistances of the analysed girders are determined and the structural behaviour under the combined loading situation is investigated. The research work is completed according to the following research strategy:

- literature overview in the topics of (i) previous investigations on M-V; M-F and F-V interaction behaviour, (ii) previous analytical and numerical investigations of the M-V-F interaction behaviour of steel I-girders,
- development of an advanced numerical model based on shell elements with variable geometry and variable loading conditions. Investigation of the structural behaviour under the different loading conditions and under the combined loading situation,
- verification of the numerical models based on test results,
- numerical parametric study to investigate the effect of the different geometric parameters on the interaction behaviour,
- comparison of the numerical results to the M-V-F interaction equation proposed by Braun and Kuhlmann [2],
- statistical analysis based on the large number of numerical calculations to determine the safety level of the new M-V-F interaction equation.

There is a huge number of previous investigations related to the M-V, M-F and V-F interaction region separately. Large amount of experimental and numerical investigations are made to investigate all the three interaction planes and to develop design interaction curves. The most important investigations found by the authors in the international literature are the followings: Sinur [7], Bergfelt [8], Lagerquist [9], Roberts [10], Elgaaly [11], Ungermann [12], Johansson and Lagerqvist [13] and Graciano et al. [14]. Elgaaly [15], Oxfort et al. [16] [17], Zoetemeier [18], Roberts et al. [19], Kuhlmann and Braun [2]. Based on the previous investigations on the M-F and V-F interaction fields and based on the results of the previous numerical calculations Braun and Kuhlmann [2] developed a combined interaction equation for the M-V-F interaction behaviour in form of Eq. (1).

$$\left(\frac{M}{M_{pl,R}}\right)^{3.6}+\left(\frac{V-0.5\cdot F}{V_R}\right)^{1.6}+\left(\frac{F}{F_R}\right)\leq 1.0 \tag{1}$$

The relevant interaction surface is illustrated in Fig. 5, which fit the requirements in the M-F and V-F planes, but no verification was done in the 3D domain. Therefore the aim of the current research is the verification of the new M-V-F interaction surface in all the three surrounding planes (M-F; V-F; M-V) and also in the 3D domain for various girder geometries.

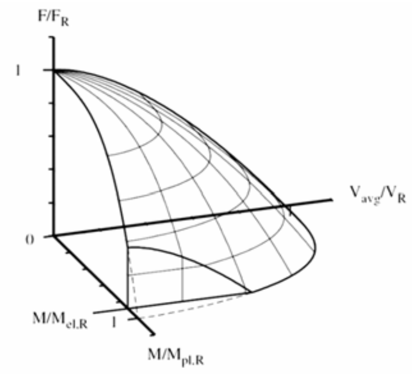

Fig. 5. Combined M-V-F interaction surface [2].

An independent research activity was executed by Graciano et al. [3] on the same research field. The final conclusion of Graciano et al. was that the new M-V-F interaction curve developed by Braun and Kuhlmann [2] gives a good approach of the calculated resistances; all the results of this study were on the safe side. Therefore the aims of the current research are to extend the previous investigations made by the authors mentioned above at the following points:

- execute a large numerical parametric study to verify the new M-V-F interaction equation in a larger parameter range,
- evaluation of the new interaction equation on the bases of the pure resistances calculated by GMNI analyses, and by the relevant resistance models of the EN1993-1-5 [1].

4. Improved design method development

4.1. Developed numerical model and numerical parametric study

The developed numerical model is based on a full shell model using four node thin shell elements. A detailed overview on the numerical modeling and the finite element calculations can be found in the MSc thesis of Alcaine [20]. The ultimate loads are determined by geometrical and material nonlinear analysis using equivalent geometric imperfections (GMNIA). The background of the numerical model development is the test results of the COMBRI research project [6]. The tests were carried out at Luleå Technical University (Sweden) having the aim to intend to quantify the effect of shear force on the patch loading resistance for welded I-girders. In case of these tests the analyzed girder was subjected by combined bending, shear and patch loading, therefore the results of these tests are optimal for the verification of the developed numerical model. The verification is made by the comparison of the results obtained in the experimental program and the numerical calculations. The difference between the measured and calculated ultimate load is 1.6% which is assumed as a good agreement. Based on the verified numerical model a numerical parametric study is conducted. To be able to validate the new M-V-F interaction surface the numerical simulations have two aims. The first aim is to determine the pure bending, shear buckling and patch loading resistances of the analysed girders. These values are the bases of the evaluation of the results under the combined loading situation. Expediently, the determination of the pure resistances is made with simplified models, which are developed only for the pure resistance development. The geometry of these simplified models and the observed typical failure modes are shown in Fig. 6.

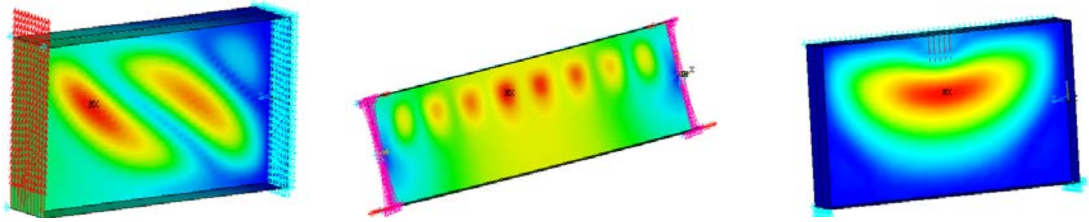
a, shear buckling type failure b, bending type failure c, patch loading type failure

Fig. 6. Applied numerical models to determine bending, shear buckling and patch loading resistances and observed failure modes.

The second aim is to study the steel I-girders under the combined loading situations. All the analyzed interaction types, namely the M-F; V-F; M-V and M-V-F interaction behaviour are analyzed on the same geometry by varying the applied internal forces. The applied loads on the girders are varied according to the internal force diagrams to be analyzed. The strategy of the investigation is the following. In the first step for each model the bending, shear buckling and patch loading resistances are determined. These are the corner points of the 3D interaction equation. After it the applied shear force is fixed by a constant value, and the ratio of the bending moment and transverse force is varied. In the next step the applied transverse force is fixed as a constant value and the ratio of the bending and shear forces are changed. Using this strategy the whole interaction domain is covered quasi-uniformly. Eleven types of girders with different geometries are investigated in frame of the numerical parametric study. 33 numerical simulations are carried out to define the "pure" resistances and the points in the 3D M-V-F interaction domain. A total of 363 calculations are carried out in frame of the MSc thesis of Alcaine [20]. From the previous studies the database of Braun [2] is also used and evaluated in the 3D domain, to get a larger database to the evaluation of the numerical calculations (175 additional calculation results).

4.2. Proposed design method for M-V-F interaction

The results of the numerical calculations are evaluated according to the FEM based resistances (Fig. 7) and according to the standard resistance models of EN1993-1-5 [1] using the plastic bending resistance and the latest improvement of the patch loading resistance proposed by Chacón et al [21], [22] (Fig. 8). The 3D plot of the numerical results and the proposed interaction surfaces are shown in Fig. 7-8. The only difference between the two diagrams are the reference resistances.

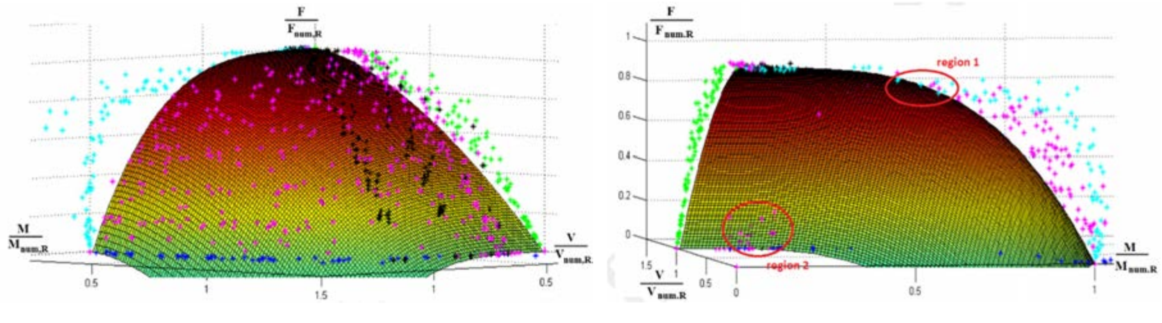

Fig. 7. Evaluation according to resistances determined by numerical simulations.

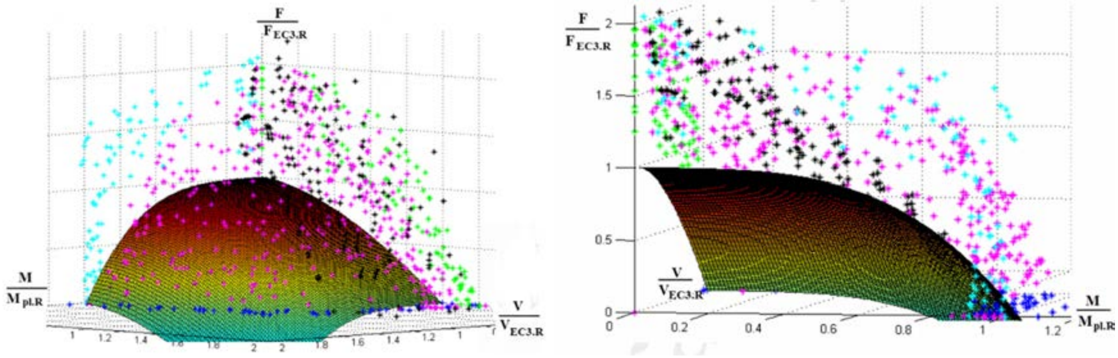

Fig. 8. Evaluation according to resistance models of EN 1993-1-5 (using $M_{pl,R}$ and patch loading resistance model of Chacón et al).

Results in Fig. 8 show that no points are inside of the interaction surface (except of in the cut of range). It means that using the resistance models of EN1993-1-5 [1] and the latest proposal for the patch loading resistance model of Chacón et al. [21] and the plastic bending resistance in the interaction equation, all the points are on the safe side, the new interaction equation can be used with adequate safety. Statistical evaluation is also performed to evaluate the safety level of the new M-V-F interaction equation. The results of the statistical evaluation are summarized in Table 1. The first evaluation method uses the FEM based resistance models (bending, shear and patch loading resistances according to numerical calculations), and the second evaluation method uses the resistance models of EN 1993-1-5 (using $M_{pl,R}$) and the latest proposal for the patch loading resistance model of Chacón et al.

Table 1. Statistical evaluation for girders without longitudinal stiffeners.

	Method 1	Method 2
mean value	1,2959	1,4146
standard deviation	0,2107	0,1734
lower 5% fractile	0,9503	1,1303

It can be seen from the statistical evaluation, that the calculation according to the Eurocode based design method (Method 2) results in adequate safety for the new M-V-F interaction equation. This evaluation proves the applicability of the interaction equation proposed by Braun and Kuhlmann [2].

5. Conclusions

The proposed M-V-F interaction curve (Eq. 2) gives a good lower bound interaction surface to the numerical results, if the bending, shear and patch loading resistances are calculated based on EN1995-1-5 [1] resistance models using the plastic bending resistance in the interaction equation. In this case all the calculation results are outside of the interaction surface for longitudinally stiffened and unstiffened girders as well. It means that all the results are on the safe side and the accuracy of the new M-V-F interaction equation is adequate. Based on the evaluation of more than 900 numerical calculations, the applicability of the interaction equation is proven in the current investigations.

$$\left(\frac{M}{M_{pl,R}}\right)^{3.6}+\left(\frac{V-0.5\cdot F}{V_R}\right)^{1.6}+\left(\frac{F}{F_R}\right)\le 1.0 \tag{2}$$

The calculations proved that the assumption of Braun to use the plastic bending resistance in the interaction equation is adequate. The results give a good fit to the interaction equation in the main part of the interaction region. Based on the statistical evaluation the mean value and the standard deviation are also smaller if the plastic bending resistance is used in the interaction equation. The new M-V-F interaction curve can be used with current EN1993-1-5 [1] resistance models with adequate safety.

Acknowledgement

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