Numerical modeling for incrementally launched steel bridges. Application to patch loading assessment.

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Abstract

In this paper, a realistic nonlinear 3D simulation of an incrementally launched steel bridge girder is presented. Thus, this work is aimed to show the capabilities of the presented numerical model in structural verifications, specially for the patch loading phenomenon (or concentrated loading). Hence, the study is focused on the patch loading field, a structurally complex phenomenon which typically appears in incrementally launched steel I-girders. The presented realistic simulation, which is based upon an experimentally calibrated numerical model, may provide relevant information at design stage. The predictive capabilities of the model for inferring the potential failure due to patch loading are depicted.

Keywords: Incremental launching method, steel bridges, patch loading, structural verification.

I. Introduction

The incremental launching method

The Incremental Launching Method (ILM) is one of the so called self-resistant bridge construction methods, meaning that no framework is required. This allows the construction in inaccessible locations (deep valleys or rivers) and minimizes the surroundings affectation. In the ILM, once the construction of abutments and piles has been completed, one section of the slab is assembled in one, or eventually both, sides of the bridge. Once this section has been assembled, it is pushed forward and the cycle starts again until the slab is completed. The first bridge constructed by means of the ILM was the Kufstein bridge (Germany) in 1965.

The ILM requires a lot of specific auxiliary technologies such as launching bearings, hydraulic jacks or high precision topographic equipment. This technologies have hugely evolved in the last decades, making the method competitive in front of other construction techniques. This fact has allowed the application of the ILM in extremely large structures, such as the Millau viaduct (2004). More information regarding the ILM can be found in [1].

In the ILM, the structural scheme continuously changes during the launching, yielding in a variation in both the boundary conditions and loads at each time step. This has been typically handled solving one static problem for each time step. Some recent work aimed to model the whole launching as a unique problem can be found in the literature. For instance, Xu and Shao recently developed a new beam element that is able to consider these non-constant B.C. [2]. Despite this, numerical implementations under a realistic and transient view of the problem are still pending in the literature. Hence, the necessity of new models that allow the assessment of complex structural phenomenon such as patch loading arises.

Patch loading phenomenon

Historically, one of the most studied topics within the steel engineering field has been the instability failure in slender structures. This also applies in compressed panels under concentrated loads, which is the case for launched I-shaped girders over a pile. Therefore, the ultimate load in robust panels might come from a yielding phenomenon, whereas in slender panels it might come from an instability

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mechanism. The value of such critical patch loading load has been widely studied in recent years (references from [3] to [6]).

As has been commented before, patch loading typically affects I-shaped launched steel girders. Moreover, patch loading response is purely three dimensional. Therefore, numerical models aimed to reproduce the launching of I-shaped steel girders in a realistic way are necessary. Hence, a 3D realistic approach of the problem is mandatory since traditional bar models are unable to reproduce these purely three-dimensional phenomena.

II. Simulation

Main features

A FE numerical model has been used as simulation tool. The model, implemented in the commercial software Simulia Abaqus, reproduces realistically the movement of one steel girder over a launching platform towards the intermediate and end supports. The geometry of the simulated bodies was discretized using linear shell elements. Shell elements allows to realistically reproduce 3D geometries in where one dimension is much smaller than the others (in this case the thickness of the plates). Moreover, shell elements allow developing local or global buckling phenomena, provided an initial geometrical imperfection that triggers the 2nd order behavior. Such imperfection was taken according to EN1993-1-5-C recommendations. The supports were modeled as rigid and frictionless surfaces connected to the ground on which the steel plates are able to slide and/or transmit contact stresses but conversely, are not able to penetrate through.

The material non-linearity for metallic materials is based upon an ideal elastic plastic constitutive equation with isotropic hardening. For multi-axial stresses, the von Mises criterion is taken. Regarding the boundary conditions, all the DOFs in the rear part of the beam are imposed to be 0 except the one in the launching direction, whose value equals the launching distance. Furthermore, an auxiliary boundary condition was taken into account for avoiding the horizontal misalignment of the flanges. As a consequence, the lateral torsional buckling mode of failure is not considered in this work. Table 1 collects the main features of the model. More information can be found in [7].

Table 1: Features summary.

Model features	
Procedure	Geometrically non-linear
Structure	Two spans (20-30 m)
Cross section	Stiffened I-shaped beam
Load	Only self-weight
Material features	
Steel class	S355
$E\ (N/mm^2)$	$2.1e+11$
ν	0.3
$\rho\ (kg/m^3)$	7850
$f_y\ (N/mm^2)$	355
$f_u\ (N/mm^2)$	490
Interaction features	
Normal	No penetration. Separation allowed.
Tangential	Frictionless
Mesh features	
Type	Structured
Nodes	≈ 17000
DOFs	≈ 102000
Element	4-noded linear shell (S4R)
h	100 mm

Validation

The numerical model was validated throughout a small-scale study performed by the authors and other co-workers in previous works. The numerical model of the small-scale laboratory test was reproduced with beam elements as well as with shell elements. Such small-scale experimental test consisted in a rectangular steel plate launched from one continuous platform to a pair of supports, generating a two-spanned continuous beam. The experimental and numerical results (both beam and shell models) showed similar results. More precise information regarding the validation of the model can be found in [7] and [8].

Parametric study

An amount of 20 large scale models were simulated. The set of simulations are composed by a systematic variation of the web thickness $t_w = [4\ 6\ 8\ 10\ 12]\ mm$ and the bearing length $s_s = [50\ 625\ 1875\ 2500]\ mm$ was performed. The obtained results were exploited for the sake of understanding the patch loading phenomenon in a realistic model. Flange width $b_f = 600\ mm$, web height $h_w = 1200\ mm$ and stiffeners distance $a = 2500\ mm$ were held constant. Figures 1 and 2 depict the geometry of the model.

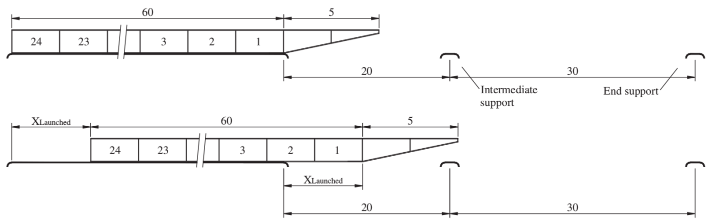

Figure 1: General geometry sketch.

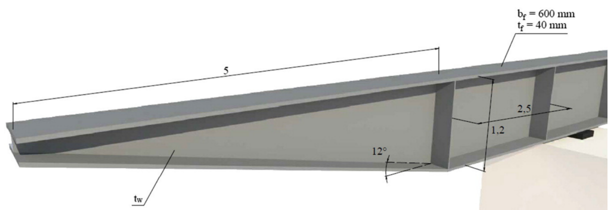

Figure 2: 3D representation of the front part of the modeled beam.

III. Results

General overview

Table 2 collects a convergence summary of the parametric study. The average computational time is 19.63 hours. Studying the obtained results, models 1, 2, 3 and 4, which are the ones corresponding to $t_w = 4\ mm$, present unrecoverable deformations in the central part of some web panels. This large deformation explains the lost of convergence before the launching completion in models 1 and 2.

Figure 3 depicts the maximum vertical deflection of the launching nose for $t_w = 6\ mm$ and several s_s values. The evolution of the deflection is the one expected for a cantilever until the beam reaches the first pile (20 m), where the deflection is fully recovered and the structural scheme varies to a clamped-simply supported beam with a cantilever in its right end. Thus, as long as the launching continues, the deflection starts to grow again. Its also worth to point out that the maximum deflection varies according to s_s, for $s_s = 2500\ mm$ $\delta_{max} = 227.4\ mm$ meanwhile for $s_s = 50\ m$ $\delta_{max} = 295.2\ mm$, which approximately represents a 30% increase.

In this section an general overview of the results has been presented. More general results and some applications to structural health monitoring can be found in [7] and [9].

Table 2: Parametric study results summary.

Model	t_w	s_s	time (h)	$x_{Launched}$
1	4	50	39.97	47.95
2	4	625	17.89	47.1
3	4	1875	21.50	50
4	4	2500	20.86	50
5	6	50	34.61	50
6	6	625	14.84	50
7	6	1875	16.52	50
8	6	2500	16.44	50
9	8	50	40.67	50
10	8	625	12.25	50
11	8	1875	17.53	50
12	8	2500	13.94	50
13	10	50	27.23	50
14	10	625	10.96	50
15	10	1875	12.39	50
16	10	2500	12.39	50
17	12	50	27.53	50
18	12	625	10.90	50
19	12	1875	12.29	50
20	12	2500	11.94	50

Patch loading assessment

Figure 4 depicts the maximum out-of-plane displacement for all panels and $s_s = 50\ mm$. As can be seen, for all models with $t_w \geq 6\ mm$ there is a clear trend in the maximum displacement. However, for $t_w = 4\ mm$ this trend is abandoned prematurely for panels 8 up to 12, meaning that an instability phenomenon is affecting to those panels.

Once arrived to this point, it is interesting to show some results regarding the stresses for the assessment of the local unrecoverable deformations. Figure 5 depicts for $t_w = 4\ mm$ and $s_s = 50\ mm$ the evolution of the critical panel (12) over the intermediate support. Firstly, no local stresses are observable in the panel, meaning that the contact force is directly transferred to the support. For the next increment, concentrated stresses over the yielding limit ($f_y = 355\ N/mm^2$) can be observed, leading to unrecoverable strains and considerable out-of-plane displacement. This behavior is even worse in the third stage, when the support is aligned with the mid axis of the panel. At the fourth stage, some local yielding can be observed in the bottom left part of the panel. Finally, the state of the panel when it leaves the support is depicted and the remaining distribution of unrecoverable deformations is noticeable.

Once the patch loading results have been presented, it can be asserted that the model is able to reproduce this structural phenomena and its failure modes. Thus, the presented simulations may become in a design tool for assessing the failure due to the interaction of shear, bending and patch loading. More extended results regarding the exploitation of the model from the patch loading point of view can be found in [7] and [9].

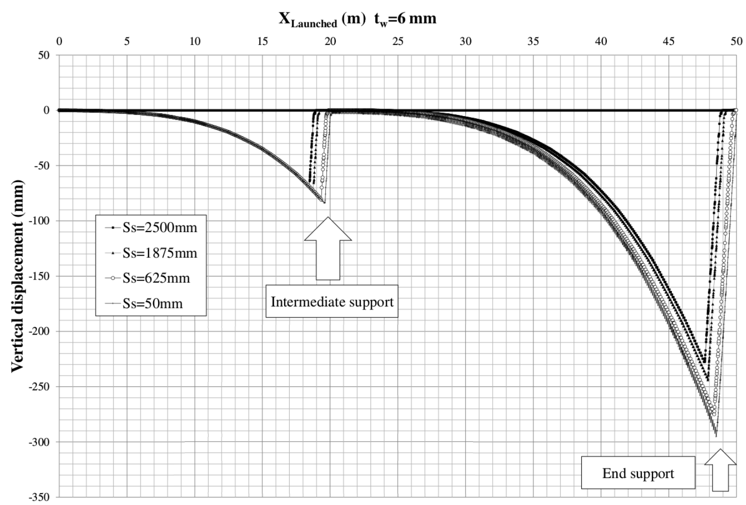

Figure 3: Maximum vertical deflection evolution along launching for $t_w = 6\ mm$.

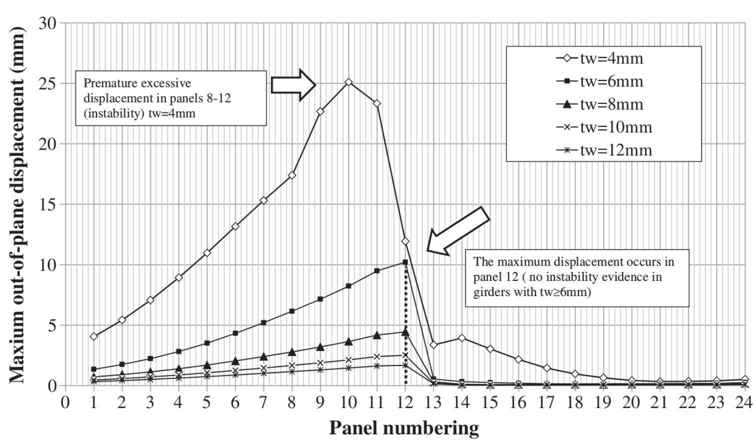

Figure 4: Maximum out-of-plane displacement for all panels and $s_s = 50\ mm$.

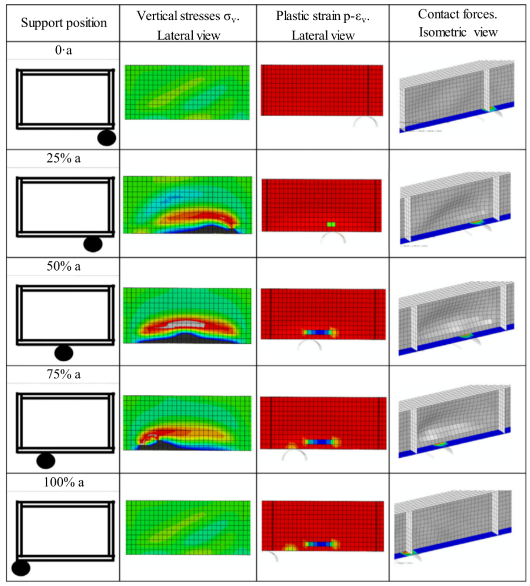

Figure 5: Patch loading assessment. Panel 12 over support ($t_w = 4\ mm$ and $s_s = 50\ mm$).

IV. Conclusions

In this work a 3D realistic non-linear simulation of an I-shaped steel girder incremental launching procedure is presented. During this process, a continuous monitoring of displacements, strains and stresses as well as contact forces is obtained as a result. These magnitudes can be extracted from the model at any increment and at any point of the whole model. The numerical model involves three sources of non-linearity: geometrical, material and the boundary conditions.

The model has been exploited from the patch loading assessment perspective. Thus, the model can used for:

- detecting a potential failure due to concentrated loading during launching. The continuous nature of bridge launching implies that high reactions occur at unstiffened cross-sections. The model is able to predict this and might be useful for structural designers.
- the better understanding of the behavior of a traveling load over an unstiffened panel. The simulation is able to predict in a such realistic way the patch loading phenomena and might be used for teaching or research purposes.

Further refinements of the presented work are being carried out. Lateral torsional buckling, which may condition the ultimate load must be taken into account. Indeed, the authors are working in this particular field by means of the launching of curve beams. Moreover, the application range of the model can be spread implementing other potential stress sources such as thermal loads or structural imperfections. Finally, it is also interesting to point out that some real data is still necessary for a finer calibration of the model.

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