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Safety assessment of bridge decks under exceptional traffic loads

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Abstract

Exceptional traffic loads, or overweight loads, represent a critical issue for many of the existing reinforced concrete bridges on the Italian motor-way network, as these bridges were designed for different loading conditions to those imposed by today's overweight convoys. Furthermore, as these structures were mainly built during the twenty-year period between the 1950s and 1970s, deterioration due to chloride-induced corrosion caused by the use of deicing salts is often observed on both piers and deck members. This phenomenon has a significant impact on the structural integrity and load-bearing capacity of the structural elements. Consequently, in-depth structural assessments are required. In Italy, the current standards on these issues are the Italian Design Code (NTC 2018) and the Existing bridges Guidelines 2022 (LG22). In this paper, the structural performance of existing bridge decks under exceptional traffic loads is assessed by applying the principles outlined in NTC 2018 and LG 2022.
The results of this assessment are also compared with those obtained from another advanced methodology based on nonlinear static (push-down) analysis, which considers the nonlinear behavior of materials. By using the push-down analysis, the structural behavior under incrementally applied loading steps can be monitored, the activation of inelastic hinges can be detected, and, from the obtained force-displacement capacity curves, the failure load (or failure load factor) can be determined as well. The results obtained using the commonly adopted linear analysis are compared and discussed with those coming from the push-down procedure. This is achieved by applying the two different approaches to various deck configurations.

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1. Introduction

Existing bridges represent strategic assets for the European economic system, Biondini and Frangopol (2012). Ensuring their structural safety under increasing traffic loads, Miluccio et al. (2021), and seismic demand, Zucca et al. (2023), is mandatory especially in possible inadequate maintenance conditions for materials' degradation due to environmental exposure, Zhou (2014). In this study, the structural response of n.8 existing Italian girder-bridge decks subjected to exceptional traffic loads is investigated through nonlinear static analyses. The results are compared to the safety verifications prescribed by the Italian Design Code (NTC2018) and Existing bridges Guideline (2022). The aim is to highlight the role of nonlinear material properties under vertical loads with particular attention to the stress's redistribution interesting each structural components of the girder decks. The evaluation of the safety reserve of single bridge's decks is a key parameter for the overall management and planning of structural retrofitting interventions. In the following, Section 2 describes the nonlinear analyses here proposed, Section 3 introduces the case studies in terms of geometrical features, loads and materials whereas Section 4 reports the nonlinear analyses' results in terms of Load Factors. They are also compared to the ones obtained by the linear approach of the Italian code NTC2018. Finally, Section 5 remarks on the main conclusions.

2. Nonlinear Push-Down analysis

Bridges decks are girder systems designed to withstand traffic and exceptional loads, Givonetti et al. (2023). The structural failure mechanisms are not usually instantaneous due to the intrinsic redundancy of the structural configuration. Otherwise, if a reinforced concrete (RC) deck's elements should exceed the elastic limit, stress redistribution on the decks' members would occur for RC's nonlinear properties, Kheyroddin and Mortezaei (2007) and Kim et al. (2009). Therefore, the response to exceptional traffic loads can be studied by adopting reinforced concrete nonlinear properties and performing nonlinear static analyses here referred as push-down analyses, Khandelwal and El-Tawil (2011) and Givonetti et al. (2024). This kind of analysis consists of an incremental load applied to the deck implemented in the finite element model (FEM). Consequently, the nonlinear response of the elements can be monitored step-by-step. In the present research, Midas Civil (version 1.1-2025) is adopted for the structural modelling and the execution of the analyses. The generic deck is modelled by beam elements with the monodirectional, multidirectional or fixed supports according to the original design documents, Hambly (2014). The nonlinear response of the deck is simulated by introducing plastic hinges by means of moment-curvature relations, Powell (2005) and Derseh and Mohammed (2023). A specific fiber code has been developed in Phyton, Givonetti et al. (2023), to obtain the moment-curvature diagrams of the investigated structural sections. By Opensees, Marmo et al. (2021), nonlinear materials properties are assigned to the fibers of the girders and cross beams sections. The moment-curvature diagrams obtained with this tool are then implemented in the FEM by linearizing them. Push-down analyses are performed, and the results are expressed in terms of load factor, defined as the multiplier of the allowable load for the deck, accounting for material nonlinearity and for redistribution of internal forces among the deck elements, Fallon et al. (2016). To correctly perform valid push-down analyses, it is mandatory to fix the number of hinges and their position based on the structural configuration of the deck.

3. Case studies

3.1. Features of the decks

The 8 RC analyzed decks are part of existing Italian bridges built around the 1960s. They differ by themselves for span, width, number of the beams and crossbeams, and spacing between the structural elements, Table 1. Their material properties are reported in Table 2. In the moment-curvature fiber code, nonlinear properties are attributed to the fibers of the generic beam's simplified section (Fig.1) the Kent and Park model to the concrete, Park et al. (1972);

the bilinear model with hardening to the steel bars; and the Menegotto-Pinto model for prestressing steel, Menegotto and Pinto (1973).

Fig. 1. Beam cross section of the existing bridge (on the left) and Fiber discretization of the beam cross section (on the right)

Table 1. Deck properties of the case studies

Deck number	Span[m]	Width[m]	beams [-]	Beam spacing m]	Cross-beams	Cross-beam spacing [m]
1	27.0	12.3	3	4.50	4	9.0
2	10.0	12.0	6	2.02	5	5.0
3	20.0	12.0	6	2.02	3	5.0
4	12.0	12.3	6	2.00	3	6.0
5	28.5	11.0	4	2.75	5	6.7
6	17.0	12.3	3	4.50	3	8.5
7	23.1	12.3	3	4.50	4	7.7
8	27.0	12.3	3	4.50	4	9.0

Table 2. Material properties of the case studies

Deck number	f_{cd} [MPa]	Reb.f_{yd} [MPa]	Reb. f_{ud} [MPa]	Strands f_{yd} [MPa]	Strands f_{ud} [MPa]	χy [1/m]	M_{yd} [kNm]	χ_u [1/m]	M_{Rd} [kNm]
1	23.9	331.7	500.0	1400.0	1550.0	0.0060	13900	0.0380	15641
2	27.6	438.0	503.7	-	-	0.0024	1860	0.0598	2100
3	27.3	438.0	503.7	-	-	0.0018	5400	0.0425	6210
4	11.3	426.0	489.9	-	-	0.0027	2171	0.0616	2543
5	23.8	373.9	430.0	1391.3	1600.0	0.0060	18780	0.0400	21258
6	15.9	377.8	434.5	-	-	0.0015	6750	0.0380	7952
7	15.9	377.8	434.5	1256.0	1444.4	0.0056	11040	0.0394	12699
8	15.9	377.8	434.5	1256.0	1444.4	0.0062	12360	0.0399	14175

3.2. Loads

The static loads present on the deck are structural self-weight, curbs and parapets, barriers, and paving. They vary as quoted in the historical design drawings and they are included in the initial non-linear analysis step (dead loads only), as well as the contribution of prestressing, considering the jacking tension reduced by the prestressing losses reported in the as-built historical calculation reports. The exceptional traffic load here considered consists of a 54 tons vehicle with 6 axles (3 in the tractor unit and 3 in the trailer one, respectively, Fig.2). The traffic load is introduced in FEM by forces reproducing the 54 tons overall load by adopting the specific moving tracer command present in Midas, Fig. 2.

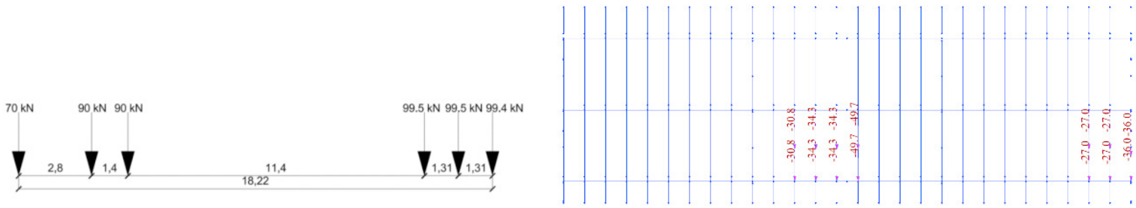

Fig. 2. Exceptional transport traffic load (on the left) and Load conversion with mobile tracer.

3.3. Plastic hinges

In the FEM, the plastic hinges with 5-segment line model of Fig.3 are introduced in critical sections where their activation can be expected (e.g. at midspan of the main girders and crossbeams, as well as in the connection zones between the girders and the crossbeams themselves). Fig. 3 also shows typical positions of the hinges for one of the case studies.

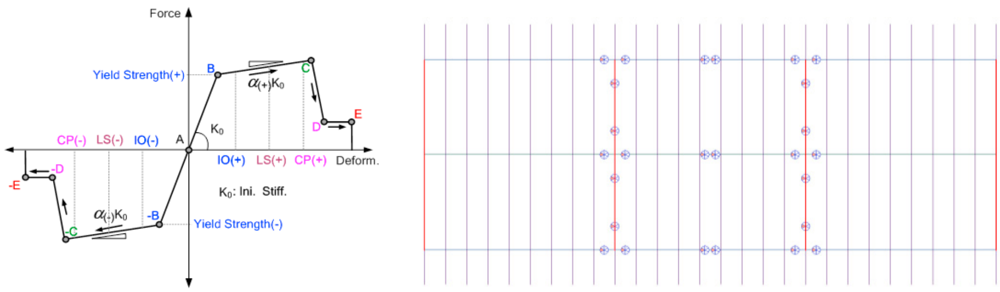

Fig.3. moment-curvature model adopted in the FEM (on the left) and Inelastic hinges distribution of a case study – plan view (on the right).

4. Results

The results obtained from elastic and push-down analyses are synthetically resumed in Table 3. They are expressed in terms of load factors considering the elastic and ultimate limit. From the elastic analysis, the results are named EL_LF_y and EL_LF_u, while from the push-down analysis the results are NL_LF_y and NL_LF_u. EL_LFy and EL_LF_u are obtained as the ratio between the residual load and the exceptional transport load, both for the elastic limit and the ultimate limit. Residual load refers to the maximum traffic load that a structural element can carry, obtained by subtracting the components of self-weight and permanent loads from the (elastic or ultimate) moment, then converting this residual traffic moment into load. In Table 3, the percentage increase in the load factor at elastic limit and at ultimate limit is reported too. The capacity curves for the 8 case studies are shown in Fig. 4. As example for viaduct number 1, the plots showing the first activation of the hinges (yielding of girder and crossbeam) and the collapse mechanism configuration (ultimate limit reached for the first hinge) are shown in Fig.5.

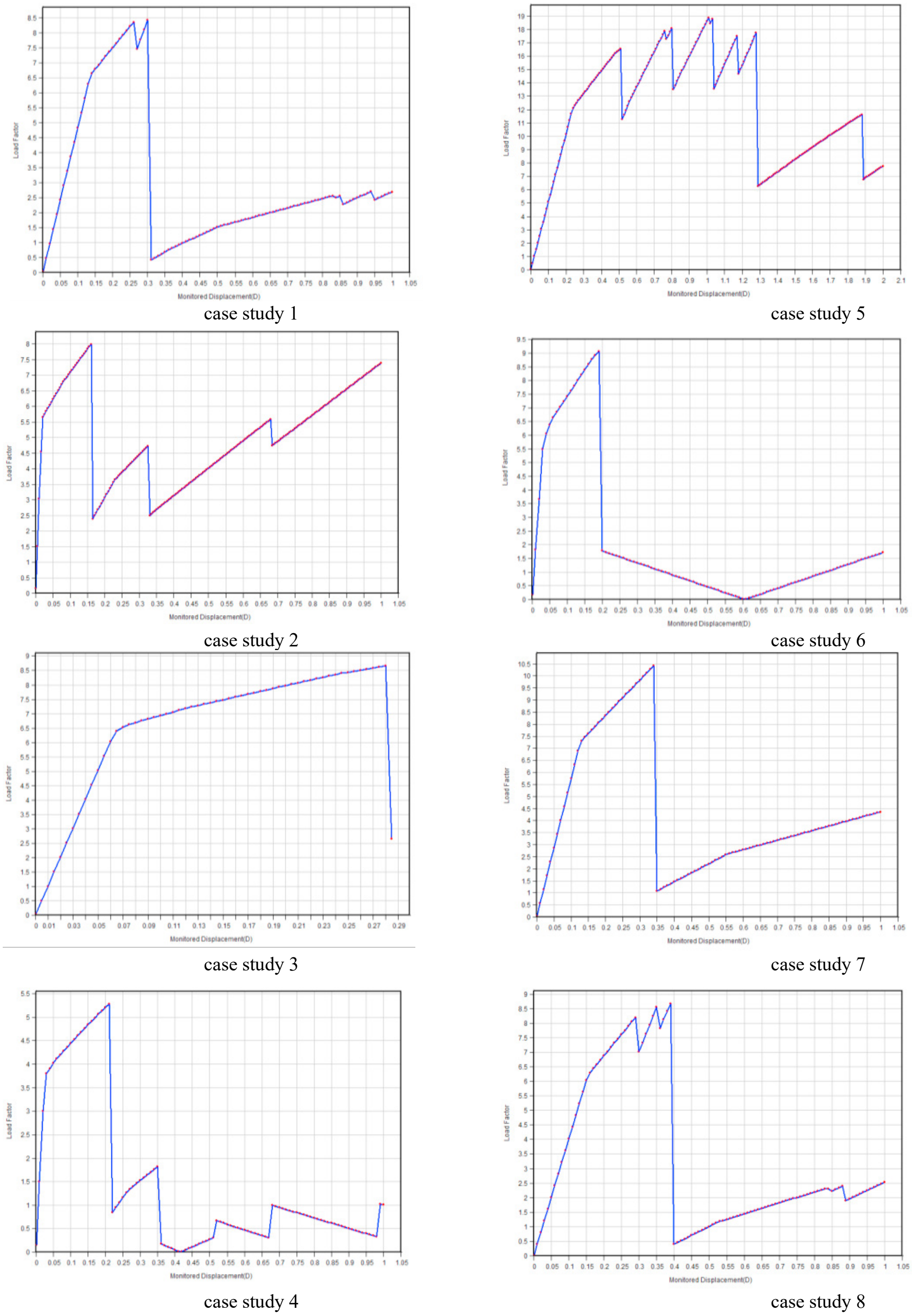

Fig.4. Capacity curves of the cases study.

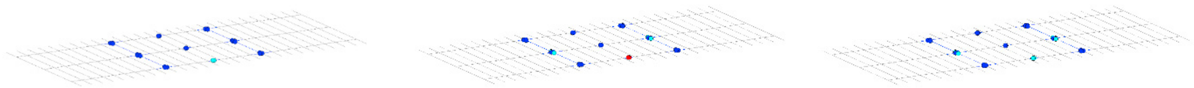

Fig.5. Viaduct n°1: first beam hinge yielding (on the left), first beam hinge collapse (at the center), first crossbeam hinge yielding (on the right). Note: the first yielding condition is represented in light blue, the collapse is represented in red, and the elastic field is blue.

Table 3. Results in terms of Load Factor (LF) in the elastic and push-down analyses, both for the elastic and ultimate limit.

Deck number	EL_LF_y [-]	EL_LF_u [-]	NL_LF_y [-]	NL_LF_u [-]	Increment y [%]	Increment u [%]
1	5.35	6.21	6.3	8.4	+15%	+26%
2	2.04	2.36	5.65	7.98	+64%	+70%
3	1.94	2.44	6.4	8.7	+59%	+63%
4	1.59	2.01	3.8	5.3	+58%	+62%
5	7.37	8.54	11	17	+33%	+50%
6	3.89	4.84	5.5	9.1	+29%	+47%
7	4.85	5.82	7.3	10.4	+34%	+44%
8	4.25	5.16	6.03	8.7	+29%	+41%

The results in terms of Load Factors previously shown in Table 3 are here graphically analyzed in relation to some significant features of the case studies, in particular: the span and the number of the main beams (Fig.6), the number of the cross-beams and the spacings between the beams and the cross-beams (Fig.7), and the number of the implemented inelastic hinges (Fig.8).

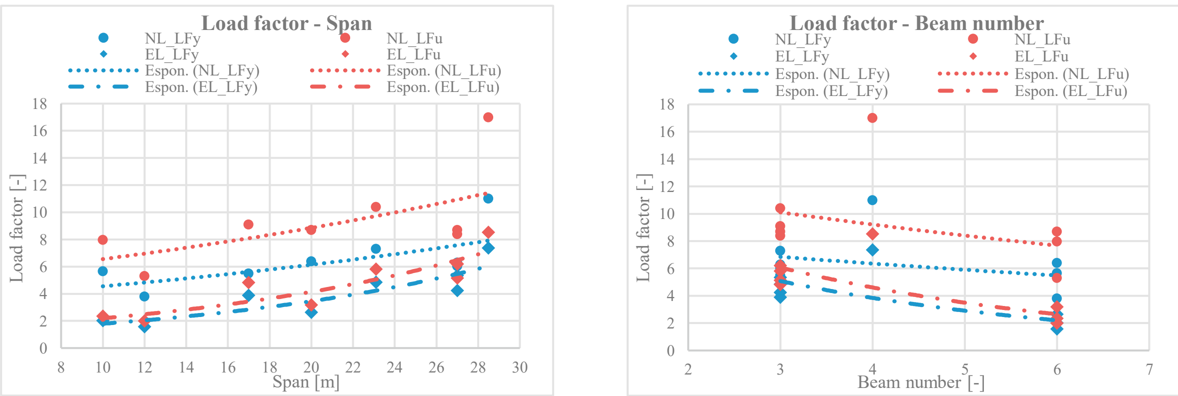

Fig.6. Relation between Load factor and deck span (on the left) and between Load factor and beam number (on the right)

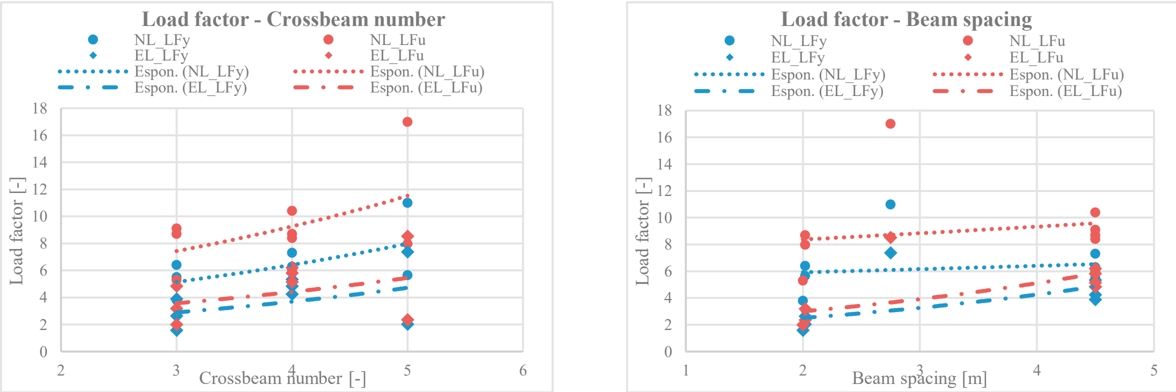

Fig.7. Relation between Load factor and crossbeam number (on the left) and between Load factor and beam spacing.

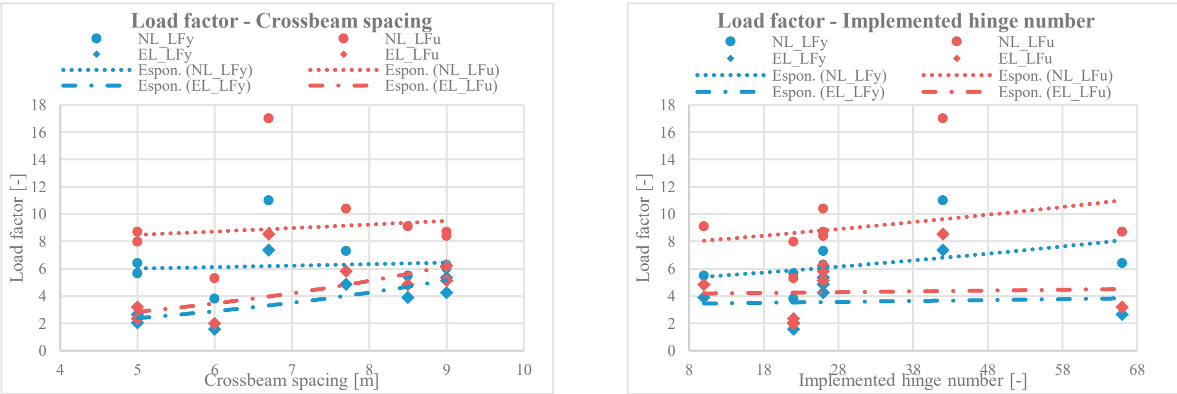

Fig.8. Relation between Load factor and crossbeam spacing (on the left) and between Load factor and number of inelastic hinges (on the right).

5. Conclusions

Puh-down analyses have been applied to the 8 different girder decks with nonlinear materials' properties implemented in the FEMs by means of plastic hinges. Since the stress redistribution guaranteed by the system beams and crossbeams structural configuration and tacking into account the nonlinear properties of the R.C. elements, the collapse load detected at the ultimate limit is about 50% higher than the one obtained by conventional elastic analysis, often indicated in the international codes. According to the parametric analysis discussed in Section 4, it can be observed that keeping constant the deck's width but increasing the span's length, an increase of the load factor values is observed. It is also due to the increase in the crossbeam's numbers. On the contrary, maintaining constant the deck's width and increasing the number of beams, the load factors generally decrease. In the analysis, when the number of plastic hinges increases, a more gradual plasticization of the deck can be observed with a significant computational effort.

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