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Fatigue assessment of steel-concrete composite highway bridges utilising a vehicle-bridge dynamic interaction methodology based on the Eurocode FLM 4

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Abstract. Nowadays, the increased weight and volume of traffic on highway bridges have accelerated deterioration processes, with fatigue induced by dynamic loads standing out as a critical challenge. In this scenario, the emergence of fatigue cracks, resulting from vehicle dynamic impacts, represents a major concern for engineers, necessitating reliable methods to assess the service life and support intervention decisions. This way, this research work proposes an analysis methodology to assess the fatigue performance of steel-concrete composite highway bridges, integrating traffic dynamic effects and the progressive pavement degradation in the dynamic structural response. The methodology develops a computational tool called VBI (Vehicle-Bridge Interaction) implemented in MATLAB and comprising an interface with the finite element program ANSYS, enabling the incorporation of complex finite element models for both the bridge and the vehicles. In this context, different scenarios based on the standard vehicle traffic prescribed by EN 1991-2: 2023 (FLM 4: Fatigue Load Model 4) are generated and adapted to statistical models of Brazilian vehicle classes. This approach allows for diverse truck configurations and weight distributions, reflecting real traffic patterns. The proposed analysis methodology was applied to a 40m span steel-concrete composite highway bridge, where a critical structural detail, mainly subjected to distortion-induced fatigue, is investigated through sub modelling techniques. The results highlight the influence of the dynamic effects and pavement degradation on the service life of the bridge structural components.

Keywords: Steel-Concrete Composite Highway Bridges; Dynamic Structural Analysis; Fatigue Assessment.

1 Introduction

The safety of highway bridges depends directly on an accurate understanding and adequate representation of traffic loads. The variability of vehicular traffic, in terms of composition, weight and distribution, represents a significant challenge for structural engineering. This type of dynamic loading causes displacements and stress variations over time, resulting in cycles of stress on the bridge's structural elements. Consequently, these cycles have the potential to expedite the development of cracks associated with the fatigue process [1].

The methodology for the dynamic analysis and fatigue assessment of steel-concrete bridges has been continuously developed over the years by the Structural Dynamics research group at the State University of Rio de Janeiro (UERJ). Recent advancements by Silva et al. [2] significantly enhanced this methodology. It now features the ability to model any type of vehicle and apply it to bridges with more varied geometries, additionally incorporating the progressive deterioration of pavement roughness.

This study utilises a Finite Element (FE) approach to model five vehicles, inspired by the Fatigue Load Model 4 from EN 1991-2 [3]. The primary objective of this investigation is to evaluate fatigue using the Hot-spot Stress Method (HSM), incorporating the complexities of vehicle-structure dynamic interaction and pavement

deterioration. For this purpose, a computational tool, VBI (Vehicle-Bridge Interaction), developed in MATLAB and interfaced with ANSYS, was utilised. This approach considers vehicle traffic at various velocities and a progressive deterioration model for the road pavement, specifically to evaluate the fatigue life of welded joints subjected to distortion-induced fatigue.

2 Analysis methodology structure

In the VBI environment, the bridge, the vehicle and a detailed sub model are initially modelled in the ANSYS (2017) software. It's important to note that the sub model is created based on data from the global model of the bridge, which implies a parametric dependency. Data integration between the ANSYS simulations is carried out via MATLAB (2021). This software is responsible for extracting essential information, such as geometry, and the mass, stiffness and damping matrices of all the subsystems. Subsequently, the dynamic equilibrium equations for the bridge and the vehicle are solved iteratively using the modal superposition and direct integration (Newmark) methods.

The steps of this analysis are presented as follows and schematically illustrated in Fig. 1, which describes the VBI routines, from the numerical characterisation of the models (global, vehicle and sub model) to the extraction of hot-spot stresses. It should be emphasized that the VBI application is based on another computational tool called Train Bridge Interaction (TBI), developed by Ribeiro [4], which was designed to perform dynamic analysis considering train-bridge interaction.

(1) Step 1: Modelling the bridge and vehicles: Vehicle and bridge models are developed based on the usual Finite Element Modelling techniques based on the use of the ANSYS. The mass and stiffness matrices of the bridge, along with the mass, stiffness, and damping matrices of the vehicle, are then exported to the VBI tool in MATLAB for the dynamic vehicle-bridge interaction analysis.

(2) Step 2: Modelling the most critical structural detail: In the second step, the critical detail model is developed in ANSYS, focusing on regions with the highest stress concentration. The sub model boundaries are placed far enough from these areas to ensure accurate results. Displacements from the global bridge model are applied to the sub model as boundary conditions, with interpolation performed at the interface between the models. The sub model coordinates are aligned with those of the global model to ensure consistency in the analysis.

(3) Step 3: Vehicle-bridge interaction dynamic analysis: Following the decoupled approach, where two different methodologies were used to solve the dynamic equilibrium equations, the dynamic equations, for the vehicle subsystem, are solved using direct integration (Newmark's method), while for the bridge subsystem, the modal superposition method was employed. The tool resolves these dynamic equations separately and makes the two systems (vehicle and bridge) compatible through an iterative method.

(4) Step 4: Modelling of the road surface roughness: The pavement roughness profile is modelled as a stationary Gaussian random process with zero mean. A progressive deterioration model is considered, based on ESAL [6] data on the vehicle composition of road traffic. When the roughness reaches a predefined limit, pavement renewal is assumed. Further details are given in Section 2.1.

(5) Step 5: Calculating fatigue damage: The fatigue assessment is performed using the Palmgren-Miner rule, which is based on the sum of linear damage, considering the hot spot stress history obtained from the structural element or region of interest. The Hot-spot Stress Method (HSM) is the approach that determines the behaviour of a welded component considering the incorporation of the stress concentration effect induced by the weld geometry.

2.1 Modelling of the road surface roughness

Based on the approach presented in [2], the road surface roughness was assumed as a zero-mean stationary Gaussian random process, and it could be generated through an inverse Fourier transformation as shown in eq. (1).

$$r(x) = \sum_{i=1}^{N} \sqrt{2 \times \Delta\Omega \times G_d(\Omega_i)} \times \cos(2\pi \times \Omega_i x + \theta_i) \quad (1)$$

Where θ_i = random phase-angle uniformly distributed from 0 to 2π; $G_d(\Omega)$ = power spectral density (PSD) function (cm^3/cycle) for the road surface elevation; and Ω_i = wave number (cycles/m). The PSD function for road

surface roughness was developed as presented in eq. (2):

$$G_d(\Omega_i) = G_d(\Omega_0) \times \left[\frac{\Omega}{\Omega_0}\right]^{-2} \quad (2)$$

Where Ω = spatial frequency of the pavement harmonic i (cycles/m); Ω_0 = discontinuity frequency of $1/2\pi$; and $G_d(\Omega_0)$ = road roughness coefficient (m^3/cycle), called RRC, whose values depending on the road class [3]. In this context, with the purpose of contemplate the pavement progressive deterioration, it is apply a model of Paterson and Attoh-Okine [5], that considering the International Roughness Index (IRI) with the values at any time after starting the road surface service, which is calculated by eqs. (3-4):

$$G_d(\Omega_0)_t = RRC_t = 6.1972 \cdot 10^{-9} \cdot \exp\left[IRI_t / 0.42808\right] + 2 \cdot 10^{-6} \quad (3)$$

$$IRI_t = 1.04e^{\eta t} \cdot [\, IRI_0 + 263 \cdot (1 + SNC)^{-5} \cdot (CESAL)_t] \quad (4)$$

Where IRIt is the value of IRI at time t; IRI_0 is the initial roughness value just after completing the construction and before opening to the traffic (adopted equal to 2.0 m/km [5]); t is the time in years; η is the environmental coefficient, which depends on dry/wet, freezing/non-freezing conditions (adopted equal to 0.023 [5]); SNC is the structural number, which is calculated from data on strength and thickness of each layer in the pavement (adopted equal to 3 [5]); $(CESAL)_t$ is the estimated traffic number in terms of AASHTO [6] 80-kN cumulative equivalent single axle load at time t, in millions, estimated using eq. (5):

$$(CESAL)_t = \sum_{v=1}^{5} f_{d,v} n_{tr,v}(t)\, F_{Ei,v} 10^{-6} \quad (5)$$

Where f_d is the design lane factor; $n_{tr}(t)$ is the cumulated number of vehicle passages for future year t; F_{Ei} is the load equivalence factor for axle category i and v is the index related to the vehicle number.

2.2 Guidelines for determining hot-spot stress

The Hot Spot Stress Method (HSM) is fundamental for fatigue assessment of structural details not covered by conventional standards. In this context, the recommendations of the International Institute of Welding (IIW) [7] are rigorously followed to ensure precision. The Finite Element Method (FEM) stands out as the ideal tool for analysing complex geometries and calculating stresses in regions with stress concentration. Thus, the use of a sub model, with a locally refined mesh, is essential to adequately represent the stresses at the detail's boundary.
From the sub model of the investigated detail, the hot-spot stress, located at the weld toe, is determined via quadratic extrapolation from three reference points. These points are situated at distances of $0.4t_w$, $0.9t_w$, and $1.4t_w$ from the edge of the weld bead, according to eq. (6), where t_w represents the plate thickness:

$$\sigma_{hs} = 2.52 \cdot \sigma_{0.4tw} - 2.24 \cdot \sigma_{0.9tw} + 0.72 \cdot \sigma_{1.4tw} \quad (6)$$

3 Structural model and finite element model of a steel-concrete composite highway bridge

In this work, the bridge structural model corresponds to a typical simply supported steel-concrete bridge deck with straight axis, spanning 13 m by 40 m and with a 0.225 m thick concrete slab (Fig. 2). The steel sections are composed by welded wide flanges made with A588 steel with 350 MPa yield strength and 485 MPa ultimate tensile strength. A 2.0×10^5 MPa Young's modulus with 0.3 Poisson's ratio was adopted for the steel girders. The concrete slab has 25 MPa compression strength with 3.05×10^4 MPa of Young's modulus and 0.2 Poisson's ratio. The numerical model developed for the steel-concrete composite bridge dynamic analysis adopted the usual mesh refinement techniques present in finite element method simulations implemented in the ANSYS computational program, see Fig. 2(b). The developed bridge finite element model used 17,542 nodes, 16,112 elements, which resulted in a numeric model with 105,252 degrees of freedom. The investigated steel-concrete composite bridge natural frequencies (f_0) and vibration modes have been determined based on numerical methods of extraction (modal analysis), through a free vibration analysis (see Fig. 3).

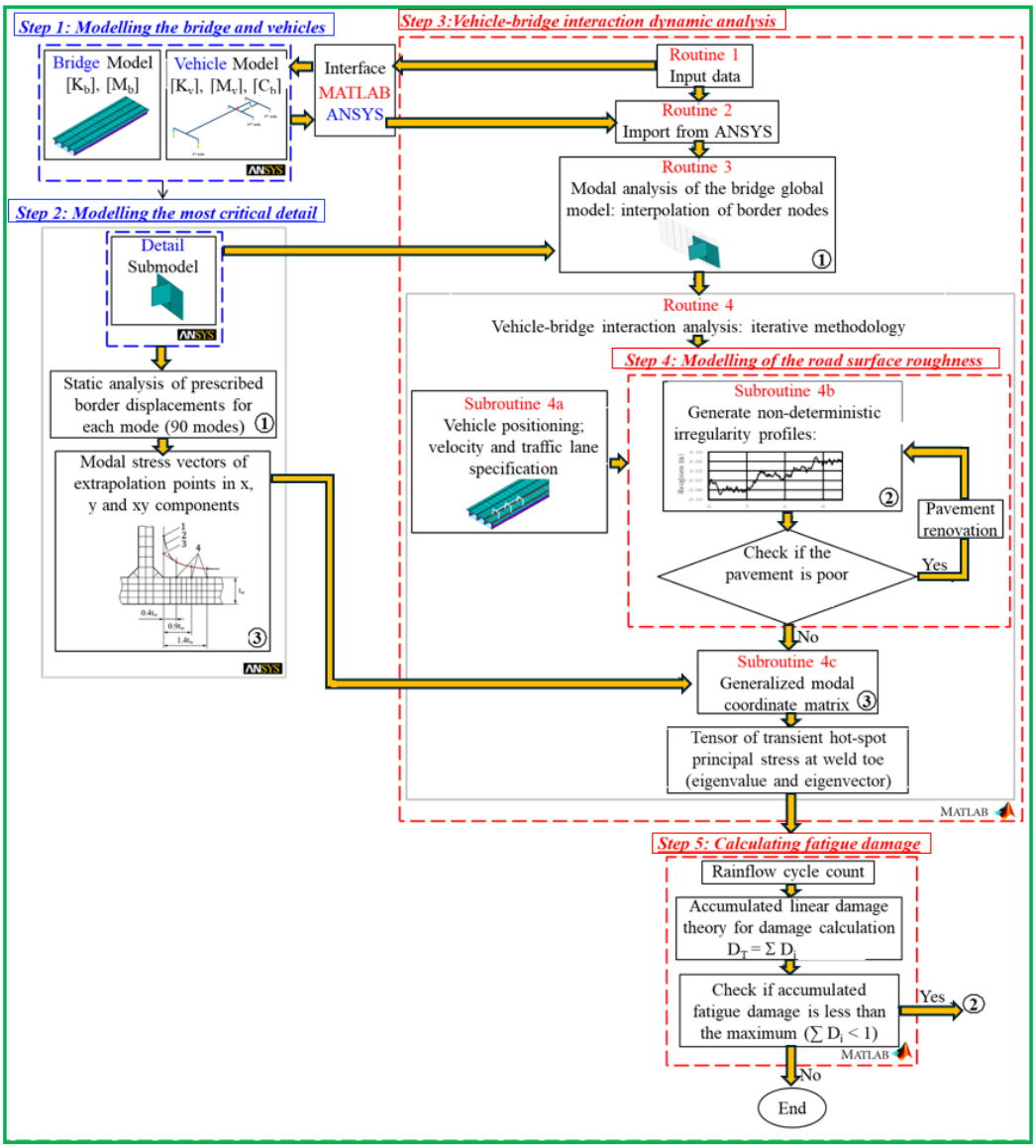
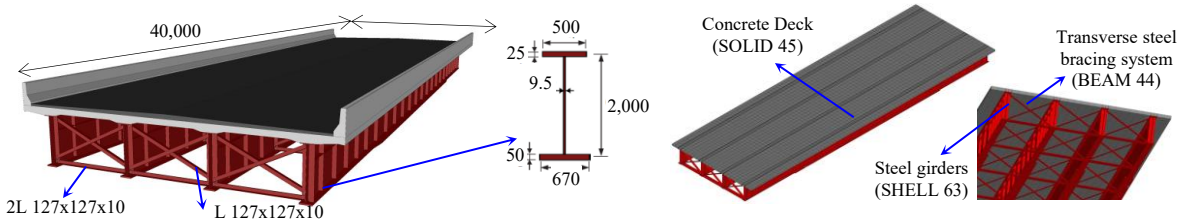


Figure 1. Flowchart of the proposed methodology: VBI tool (Adapted from Silva et al. [2]).



a) Structure design (units in millimetres) b) Finite element model of the bridge

Figure 2. Investigated simply supported steel-concrete highway bridge.

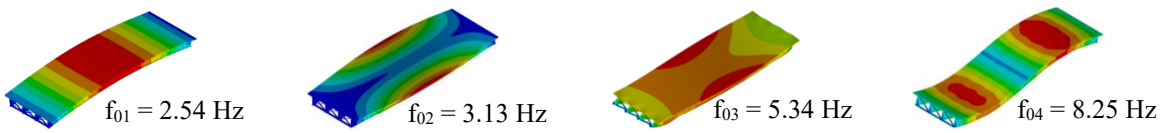


Figure 3. Vibration modes of the investigated bridge.

4 Vehicles modelling

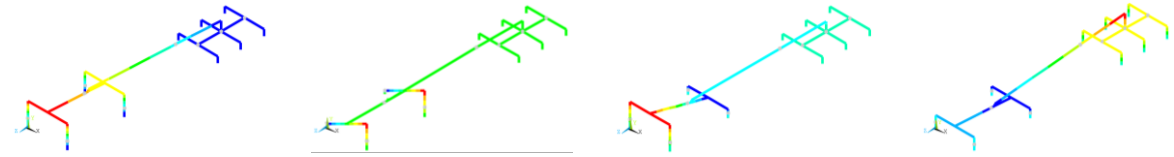
The stress spectrum generated by traffic on highway bridges depends on parameters such as vehicle geometry, axle loads, spacing, traffic composition, and dynamic vehicle properties. In this context, EN 1991-2 [3] defines Fatigue Load Model 4 (FLM4), a set of five standard lorries derived to produce the same fatigue load effects as typical traffic on European roads. The vehicles within this model, ranging from FLM4-1 to FLM4-5, have corresponding values for medium-distance traffic detailed in Tab. 1. These vehicles are similar to the Brazilian vehicle classes (2C, 3C, 2S3, 2S2, and 2C3) in terms of legal dimensions and axle loads, according to DNIT [8]. However, EN 1991-2 [3] does not consider the dynamic characteristics of the vehicles. Therefore, to overcome this limitation, the vehicle models in this study were developed using ANSYS. The BEAM4 elements were employed to simulate the vehicle body, enabling the representation of its global movements. The MASS21 elements were strategically placed to model the concentrated masses of the wheels and vehicle body. Importantly, COMBIN14 elements were used to model the spring stiffness (kN/m) and damping coefficients (kNs/m) for both the suspension and tire systems. The dynamic vehicle properties were derived from TruckSim software [9]. This approach ensures that the simulated vehicles realistically represent modern heavy vehicle behaviour. For clarity, the main dynamic properties for FLM4-3 and global vibration modes are presented in Tab. 2. and Fig. 4, respectively.

Table 1. Set of Lorries (Adapted from EN-1991-2 [3]).

Lorry	Name	Axle spacing (m)	Equivalent axle loads (kN)	Lorry percentage in traffic
	FLM4-1	4.5	70 130	40%
	FLM4-2	4.2 1.3	70 120 120	10%
	FLM4-3	3.2 5.2 1.3 1.3	70 150 90 90 90	30%
	FLM4-4	3.4 6.0 1.8	70 140 90 90	15%
	FLM4-5	4.8 3.6 4.4 1.3	70 130 90 80 80	5%

Table 2. Dynamic properties of the FLM 4-3 vehicle model.

Parameter	1st axle	2nd axle	3rd axle	4th axle	5th axle	Units
Suspension spring stiffness(k_s)	250.00	700.00		15000.00		kN/m
Tire spring stiffness(k_t)	980.00	1960.00	1960.00	1960.00	1960.00	kN/m
Suspension damping(c_s)	15.00	30.00		180.00		kNm/s
Tire damping(c_t)	2.00	4.00	4.00	4.00	4.00	kNm/s
Suspension mass	175.00	367.50	690.00	690.00	690.00	kg
Truck body mass	9108.68			37685.35		kg



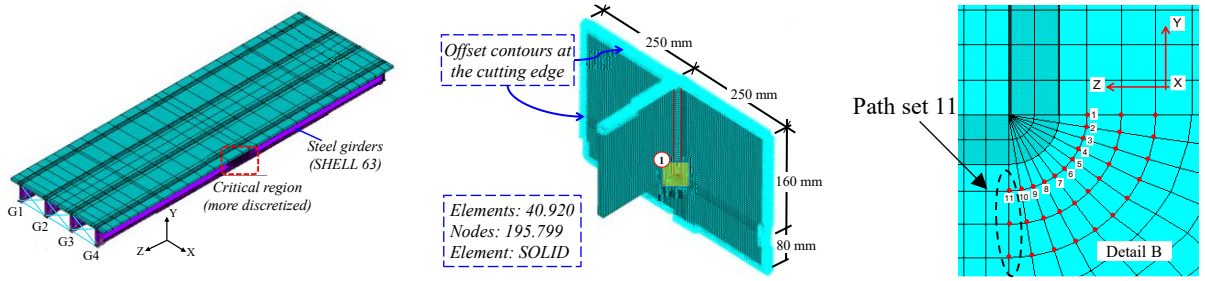
a) f_{01} = 1.43 Hz b) f_{02} = 1.88 Hz c) f_{03} = 2.18 Hz d) f_{04} = 2.95 Hz

Figure 4. Vibration modes of the FLM 4-3 vehicle.

5 Fatigue assessment

The welded structural component investigated is a web-gap that belongs to the FAT 90 [10] category, as per the hot-spot S-N design approach. Based on previous work by the authors [2], the most critical area of the bridge under investigation is located at the midpoint of the span, specifically on the extreme girder G4, see Fig. 5(a). In the present research, the right side of the stiffener welded to the web and path set 11 were chosen for investigation, as previous work by the authors [2] identified this region as frequently the most critical, see Fig. 5(c).

It should be emphasised that all vehicles travel at velocities varying from 40 km/h to 120 km/h, according to the frequencies adopted by Silva et al. [2]. The adopted total number of vehicles is 50,000 per year, considering the bridge's traffic category for local roads with low lorry flow rates, as recommended by EN 1991-2 [3]. Vehicle traffic was assumed to be exclusively in the slow lane. Additionally, three traffic scenarios were adopted: one without an increase rate ($\alpha = 0\%$) and two with increase rates ($\alpha = 1\%$ and 2%). Pavement renovation was assumed to occur when the pavement achieved a poor-quality level ($RRC_{renewal\ limit} = 64 \times 10^{-6}$).



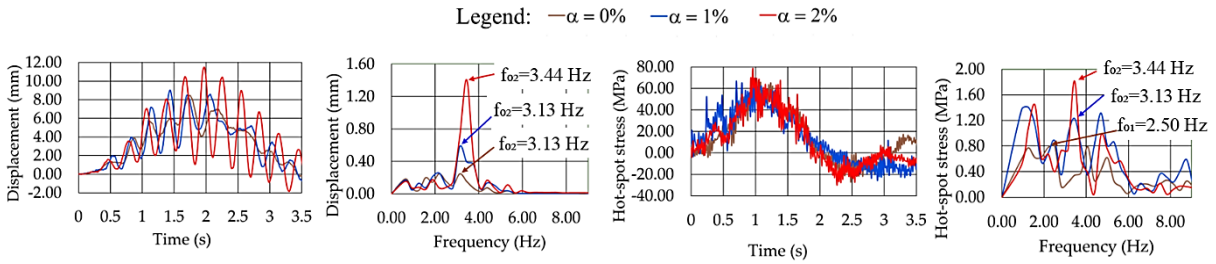
a) Indication of the detail area b) Structural detail FE sub modelling c) Right side of the detail

Figure 5. Sub model representation of the investigated detail (web-gap).

Considering the five lorries investigated in this study, the FLM4-3 exhibited the most significant structural damage and was therefore selected to illustrate the results. The displacements obtained from dynamic vehicle-structure interaction analysis at mid-span are presented in Fig. 6(a). These results consider three different traffic increase rates at a poor pavement quality level (RRC renewal limit = 64×10^{-6}). Out-of-plane hot-spot stresses obtained in the weld of the most critical component, considering the worst direction (Set 11), are shown in Fig. 6(b). As expected, for the same reference year (Fig. 6), both displacements and hot-spot stresses increased with rising traffic, owing to the greater pavement degradation. Additionally, the fatigue assessment was performed using the hot-spot stress history. For clarity, dynamic analyses were carried out annually for each of the five vehicles, and the accumulated damage was then summed to determine the fatigue life of the component, see Tab. 3.

Table 3. Fatigue life estimation.

Vehicles in operation:	FLM 4-1	FLM 4-2	FLM 4-3	FLM 4-4	FLM 4-5	**Set of Lorries FLM4**
$\alpha = 0\%$	>100 years	>100 years	66 years	>100 years	>100 years	**44 years**
$\alpha = 1\%$.	>100 years	>100 years	48 years	>100 years	>100 years	**39 years**
$\alpha = 2\%$.	>100 years	>100 years	45 years	85 years	>100 years	**35 years**



a) Vertical displacements at mid-span.

b) Hot-spot stress: right side (set 11).

Figure 6. Displacement and hot-spot stress due to the passage of the FLM4-3 vehicle at 40km/h in year 7.

6 Conclusions

In this research work, a set of five lorries appropriate to the traffic mixes predicted were modelled, inspired on EN 1991-2 [3]. These models were used in dynamic analyses for fatigue assessment, according to EN 1993-1-9 [10] recommendations, in a steel-concrete composite highway bridge. Based on the presented results, the following conclusions can be drawn.

1. The stress spectrum, and consequently the structure service life, depends on parameters such as vehicle geometry, axle loads, axle spacing, traffic composition, and dynamic vehicle properties. This highlights the importance of incorporating realistic vehicle dynamic properties. Therefore, the present approach enables a structural assessment more representative of reality and can optimize maintenance schedules and bridge designs.
2. Increased pavement degradation, driven by higher traffic growth rates, led to greater displacement amplitudes and hot-spot stresses in the investigated detail. Specifically, the service life of the detail decreased by 11% when α increased from 0% to 1%, and by 10.26% when α increased from 1% to 2%. These accurate stress responses, crucial for reliable fatigue life predictions, were obtained through the sub modelling technique, effectively coupled with the overall dynamic analysis methodology for bridge and vehicle subsystems.

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