Software Impacts 22 (2024) 100700

Contents lists available at ScienceDirect

Software Impacts

journal homepage: www.journals.elsevier.com/software-impacts

Original software publication

CALDINTAV: A simple software for dynamic analysis of high-speed railway bridges using the semi-analytical modal method

Khanh Nguyen [a,*], José M. Goicolea [b]

[a] Escuela Técnica Superior de Ingeniería Aeronáutica y del Espacio, Universidad Politécnica de Madrid, 3 Pza. Cardenal Cisneros, Madrid, 28040, Spain
[b] E.T.S.I Caminos, Canales y Puertos, Universidad Politécnica de Madrid, C Prof. Aranguren 3, 28040 Madrid, Spain

ARTICLE INFO

Keywords:
Modal analysis
Dynamic of railway bridges
High-speed train

ABSTRACT

The increasing prevalence of high-speed trains necessitates robust analysis tools to ensure the safety and reliability of railway bridges. This paper presents a user-friendly software application designed for the dynamic analysis of railway bridges subjected to high-speed train loadings. Leveraging the semi-analytical modal method, the software offers a balanced approach that combines computational efficiency with high accuracy. Key features include an intuitive interface, rapid analysis capabilities, and reliable prediction of bridge responses, facilitating design optimization and maintenance planning. This software is poised to become an indispensable tool for structural engineers, researchers, and infrastructure planners.

Code metadata

Current code version	v3.0
Permanent link to code/repository used for this code version	https://github.com/SoftwareImpacts/SIMPAC-2024-175
Permanent link to reproducible capsule	
Legal code license	GLP-3.0 license
Code versioning system used	git
Software code languages, tools and services used	Python 3
Compilation requirements, operating environments and dependencies	All necessary requirements are listed in https://github.com/khanh-nguyen-gia/caldintav/blob/main/README.md
If available, link to developer documentation/manual	https://github.com/khanh-nguyen-gia/caldintav.git
Support email for questions	khanhnguyen.gia@upm.es

1. Motivation and significance

The advent of high-speed rail systems has revolutionized transportation, bringing significant benefits in terms of reduced travel time and enhanced connectivity. However, this advancement also imposes rigorous demands on the infrastructure, particularly railway bridges. Ensuring the structural integrity and serviceability of these bridges under the dynamic loads imposed by high-speed trains is paramount for safety, reliability, and longevity. The dynamic analysis of railway bridges, therefore, becomes a critical component of the design and maintenance process [1]:

- High-speed trains exert substantial dynamic loads on railway bridges [2,3], potentially inducing vibrations that can affect structural stability and passenger comfort. Analysing these effects is crucial for preventing structural failures and ensuring safe operation.
- Many countries have stringent regulations and standards governing the design and maintenance of railway bridges. Complying with these regulations necessitates thorough dynamic analysis to verify that the bridges can withstand high-speed train loads [4].
- Understanding the dynamic behaviour of railway bridges enables engineers to optimize their design for cost-effectiveness and material efficiency without compromising safety.

Existing methods for dynamic analysis can be complex, computationally intensive, and often require extensive expertise [5]. Many traditional finite element methods (FEM) involve detailed modelling and significant computational resources, which can be a barrier for

* Corresponding author.
E-mail address: khanhnguyen.gia@upm.es (K. Nguyen).

https://doi.org/10.1016/j.simpa.2024.100700
Received 30 July 2024; Received in revised form 2 August 2024; Accepted 9 August 2024

rapid analysis and decision-making in practical engineering applications. The semi-analytical modal method offers a promising alternative for dynamic analysis of railway bridges under high-speed train loads. This method combines analytical and numerical approaches to achieve accurate and efficient solutions.

Developing a simple software based on the semi-analytical modal method will address the current challenges and harness the advantages of this approach. The proposed software will:

- Automate Analysis: Streamline the dynamic analysis process, enabling users to input bridge parameters and train loading conditions easily and obtain results quickly.
- User-Friendly Interface: Feature an intuitive interface that guides users through the analysis process, making it accessible to engineers with varying levels of expertise.
- Visualization and Reporting: Provide clear visualization of dynamic responses and generate comprehensive reports to aid in decision-making and regulatory compliance.
- Customization and Flexibility: Allow customization of input parameters and loading conditions to accommodate a wide range of bridge designs and operational scenarios.

2. Modelling background

2.1. Bridge modelling

The bridge's structure is idealized as Bernoulli–Euler beams, neglecting the effects of shear deformations. Both bending and torsional vibrations experienced by the bridges subjected to the eccentric moving loads are taken into account. The equations of motion of the bridge traversed by a train moving at a constant velocity v and section x can be obtained as:

$$m\frac{\partial^2 y(x,t)}{\partial t^2} + c_y\frac{\partial y(x,t)}{\partial t} + \frac{\partial^2}{\partial x^2}\left(EI\frac{\partial^2 y(x,t)}{\partial x^2}\right) = F(x,t) \quad (1)$$

$$mr^2\frac{\partial^2 \theta(x,t)}{\partial t^2} + c_\theta\frac{\partial \theta(x,t)}{\partial t} - \frac{\partial}{\partial x}\left(GJ\frac{\partial \theta(x,t)}{\partial x}\right) = M(x,t), \quad (2)$$

where $m,\ c_y$ and EI are the mass per unit length, the damping coefficient of bending motion and the bending stiffness of the bridge at the section x, respectively. $r,\ c_\theta$ and GJ are the radius of gyration, the damping coefficient of torsional motion and the torsional stiffness of the bridge, respectively. Both damping coefficients c_y and c_θ are considered as proportional to the mass, i.e, $c_y = 2m\zeta_{y,n}\omega_{y,n}$ for bending vibration and $c_\theta = 2mr^2\zeta_{\theta,m}\omega_{\theta,m}$. $y(x,t)$ and $\theta(x,t)$ are the vertical deflection and torsional rotation of the bridge deck. $F(x,t)$ and $M(x,t)$ are the vertical and torsional loads applied on the bridge at position x and at time t.

2.2. Train modelling

In order to simulate the moving train, in general, there are three models: the moving loads model, the moving mass model, and the moving suspension mass model. Each of them may lead to slightly different dynamic responses because of the interaction between the train and the bridge. However, different studies carried out in the literature [3,6] indicate that there is little difference in the bridge responses between the use of the different train models. In this software, there are two models that can be used as shown in Fig. 1: vertical moving loads model and the sprung masses model.

2.3. Numerical solution method

The dynamic interaction between the train and bridge forms a coupled system of differential equations of motion. To solve those equations in the time domain, the modal superposition method is employed. The motion of bridge can be expressed decoupled with a sum of modal coordinates and mode shapes, which can generate a set of decoupled equations of the generalized modal coordinates, in matrix form such as:

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = \mathbf{F}, \quad (3)$$

Depending on the type of the bridge, the boundary conditions and the presence of the bridge's skewness, the frequencies and its corresponding mode shapes of the bridge are obtained analytically via the procedure [7,8]. Then, the uncoupled matrix (3) is solved in time domain using the piecewise exact method (for moving loads model) or the β – Newmark integration method (for sprung masses model) [9].

3. Software details

3.1. Software architecture

CALDINTAV's Graphical User Interface (GUI) is constructed around one main window, divided in different tabs. In each tab, a specific part of the analysis process is dealt with, mostly by clicking buttons. In this section, a schematic overview of the GUI structure of CALDINTAV is provided as shown in Fig. 2(a) and the interaction between GUI modules and the files created during the calculation are also indicated.

The CALDINTAV main window (see Fig. 2(b)) consists of the following sections:

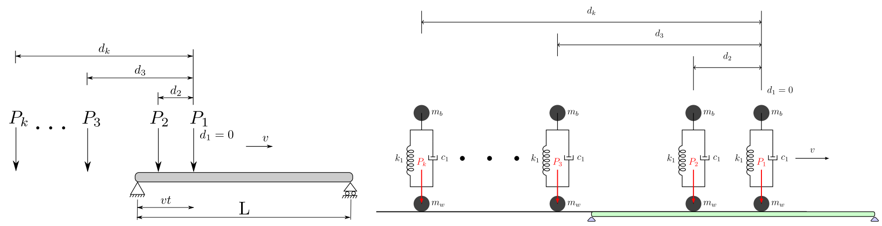
- `Project Summary`: this part of GUI assumes all input data of the work, including the bridge data, train data and analysis options.
- `‘‘Bridge’’ Tab`: This tab deals with the definition of the bridge parameters that will be analysed.
- `‘‘Train data’’ Tab`: In this tab, the users define the train model that will be used: moving loads model or train model for interaction.
- `‘‘Analysis Options’’ Tab`: This tab deals with the construction of options for the dynamic analysis. The users can choose different methods, range of train velocity, etc.
- `‘‘Global results’’ Tab`: In this tab, the users can plot the envelope responses in acceleration and displacement of the monitored point in function of train velocity for one or more selected trains. The maximum acceleration limits also are available for the comparison.
- `‘‘History results’’ Tab`: In this tab, the users can plot the time history and frequency content of the acceleration or displacement for each train at each velocity.
- `‘‘Mode Vibra’’. Tab`: This tab plots the shape of mode of vibration.

3.2. Software functionalities

The main feature of CALDINTAV is its ability to dynamically calculate railway bridge responses under high-speed train loadings, whether through moving loads or interaction models. This software performs rapid time-domain calculations, handling hundreds or thousands of scenarios to quickly check the dynamic compatibility of trains. CALDINTAV can determine dynamic displacements and accelerations along any point of the bridge length, providing detailed time-domain results. Additionally, it offers envelope results for both displacements and accelerations, comparing them against standard-defined limits. Parametric calculations for different trains and varying train speeds can be easily performed and modified, allowing for straightforward and flexible analysis.

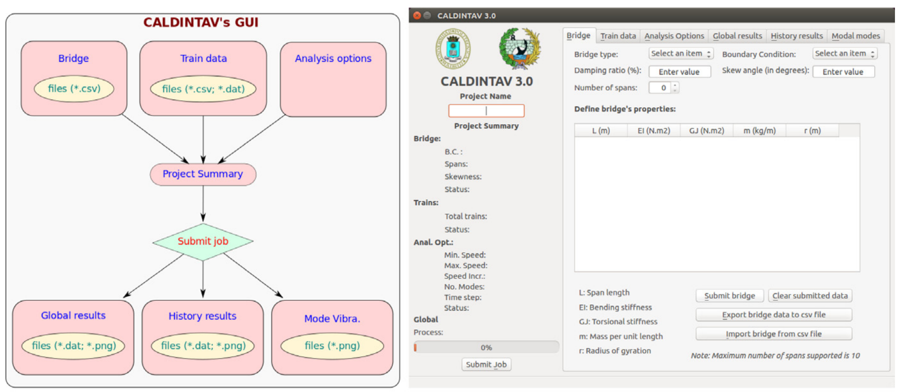
The most relevant functionalities in CALDINTAV are listed below:

- Different types of bridge (simply-supported bridge, portal frame bridge, multi-span continuous bridge) and boundary conditions are supported.
- The skewness of bridges can be introduced, therefore, the coupled bending-torsion effect is considered.



(a) Moving loads model (b) Sprung masses model

Fig. 1. Train modelling.



(a) Architecture of CALDINTAV (b) The main window of CALDINTAV's GUI

Fig. 2. CALDINTAV software.

- Ten HSLM-A train models are available, and possibility to create new proper train load model by users through the table or csv file.
- Different types of analysis method are supported, in concrete, the users can select moving loads model, interaction model and spectral methods such as DER or LIR.
- Possibility of changing the monitored point
- Parallel computing is supported.
- A detailed user manual with explanations and examples is directly accessible within the program.

3.3. *Execution of the software*

There are two types of distribution of CALDINTAV: a python package that can run on any operation systems with Python installed; and a compiled executable program for the Windows system.

3.3.1. *Python package*

CALDINTAV is a normal Python package. The installer file can be downloaded from our website. Once the download is done, it is easy to install the program using the **pip** command as following:

```
pip install caldintav.tar.gz
```

May be you need to be administrator in order to install the program. In the case that the user decompresses the downloaded file, the user can use the following command to install the program (the command is executed at the uncompressed folder):

```
python setup.py install
```

Once the package is installed, the software can be executed as:

- Open the Command Window (Terminal in Linux or Mac OS, Command Prompt in Windows system)
- Use the following command in the Command Window

```
caldintav3
```

or introducing the following commands in the Python shell

```
from caldintav import runs
runs.run_gui()
```

3.3.2. *Compiled executable program*

For the release of a compiled executable program, the user only has to decompress the downloaded file (`caldintav-v3.0.zip`). In the uncompressed folder, there is an executable program called **caldintav.exe** and to run the program, only double click on the executable file. The main window of CALDINTAV will be appeared as shown in Fig. 2(b)

4. Illustrative example

To demonstrate the capabilities of CALDINTAV, the dynamic analysis of a simply-supported bridge under five HSLM-A train models (A1 to A5) is performed. In this simulation, the bridge is 25 m of length with the following properties: $EI = 1.8735e11$ N.m^2, $GJ = 1.565625e11$ N.m^2, $m = 18437.5$ kg/m and $r = 7.608$ m. Each train model travels on the bridge with a constant speed in range of $[200, 400]$ with an increment of 2 km/h. The numerical solver uses a time increment of 0.001 s. Parallel computing is activated using 4 cpu. In total, we have 505 dynamic calculations.

Fig. 3 shows a selection of implemented graphical outputs that users can easily generate when running CALDINTAV. These graphical output include envelope of maximum acceleration and displacement, time–history of vertical acceleration, displacement of monitored point, as well as its analysis in frequency domain for each train and its speed,

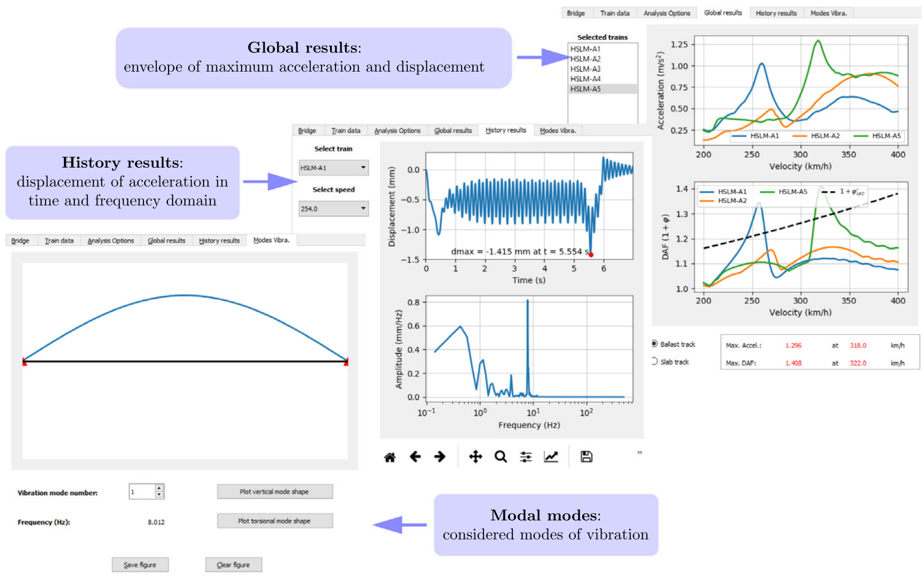


Fig. 3. Results obtained by CALDINTAV for illustrative example.

the mode shapes considered in the dynamic calculation. Furthermore, all simulation results are saved in files and accessible in the project's name folder.

It is noteworthy that completing those 505 calculations takes only approximately 65 s on a computer with a Core i7 3.41 GHz processor and 16 GB of RAM.

5. Impact and future development

Currently, the software of CALDINTAV is extensively used at Computational Mechanics Group of Technical University of Madrid (UPM). It has proven instrumental in several research studies [8,10,11], enabling massive dynamic calculations for parametric studies on the influence of skew angle, and TMD or STMD parameters on the dynamic of bridges. The software has been also integral to national research projects such as EDINPF [12] for parametric analysis of existing structures in Spain railway lines to ensure interoperability and safety. In international research project InBridge4EU [13], the software code is shared among all partners and used in all calculations to evaluate the dynamic performance of railway bridges stipulated in the Eurocodes and TSIs.

Additionally, other research groups have adopted CALDINTAV for their research study. The structural engineering group at UPM has applied it to investigate the dynamic responses of footbridge [14,15]. Specifically, the code of CALDINTAV was used to implement the vertical human crowd-footbridge interaction model for extensive parametric calculations (10000 cases). Furthermore, the CALDINTAV code is also utilized by German infrastructure operator (DB Nets AG) as main code in its ZBBD software to study dynamic compatibility between rolling stock and bridges [16]. It is should be noted that DB Nets AG published the guideline in 2016 requiring that all rolling stock entering into service on its infrastructure be checked for bridge dynamic compatibility. Consequently, with this ZBBD software, DB Nets AG can conduct this compatibility study for all German railway bridges with all trains in circulation. Notably, the programme has also been technologically transferred to the rolling stock company Talgo to develop a software for static and dynamic compatibility of Talgo's train with railway structures, demonstrating its practical industry applications.

The authors believe that this software provides engineers with a robust and precise tool for evaluating the dynamic performance of railway bridges under high-speed train loads. It offers detailed insights into vibrational behaviours, which are critical for designing safe and durable bridges. Engineers can quickly simulate various loading conditions and design configurations, leading to optimized structures that balance safety, performance, and cost. This efficiency not only accelerates the design process but also aids in proactive maintenance strategies, extending the lifespan of bridge structures and reducing long-term costs.

Although CALDINTAV offers a range of functionalities for calculations that make it accessible and highly helpful, there are still new features that could be incorporated to address emerging challenges in dynamic high-speed railway bridges. Future development could include more complex 2D train models (multi-body models), which would allow the study of the dynamic response of train components. Another enhancement could be the inclusion of track irregularities in the train-bridge interaction model, expanding CALDINTAV's ability to predict the influence of track quality on train-bridge responses. Additional features might include the introduction of elastic bearings at bridge supports and accounting for the eccentricity of train loads.

6. Final remarks

CALDINTAV represents a significant advancement in civil engineering and transportation safety. This tool empowers engineers to accurately predict and analyse the complex dynamic responses of bridge structures under high-speed train loads, facilitating more efficient and reliable bridge designs. By simplifying the analysis process, the software allows for rapid evaluation of various design scenarios, ensuring optimal performance and safety of railway bridges. Additionally, its ability to identify potential structural issues early in the design phase reduces the risk of failures and enhances the overall resilience of railway infrastructure. Ultimately, this software not only supports the growing demands of high-speed rail networks but also contributes to the creation of safer and more efficient transportation systems, fostering progress in modern infrastructure development.

CRediT authorship contribution statement

Khanh Nguyen: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **José M. Goicolea:** Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Khanh Nguyen reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The author(s) are grateful to the support of the European Union's Horizon-ER-JU- 2022-02 programme under the Grant Agreement No. 101121765.

References

[1] CEN, EN 1991-2:2003 Actions on Structures - Part 2: Traffic Loads on Bridges, European Committee For Standardization, European Union, rue de Stassart, 36B-1050 Brussels, 2003.

[2] L. Frýba, Dynamic of Railway Bridges, first ed., Thomas Telford Publishing, New York, 1996.

[3] Y.B. Yang, J.D. Yau, Y.S. Wu, Vehicle-bridge Interaction Dynamics: With Applications to High-speed Railways, first ed., World Scientific, New York, 2004.

[4] CEN, Technical Specifications for Interoperability Relating to the Infrastructure Subsytem of Rail System in the European Union, European Committee For Standardization, European Union, rue de Stassart, 36B-1050 Brussels, 2023.

[5] W. Zhai, Z. Han, Z. Chen, L. Ling, S. Zhu, Train–track–bridge dynamic interaction: a state-of-the-art review, Veh. Syst. Dyn. 57 (7) (2019) 984–1027, http://dx.doi.org/10.1080/00423114.2019.1605085.

[6] A. Doménech, P. Museros, M.D. Martínez-Rodrigo, Influence of the vehicle model on the prediction of the maximum bending response of simply-supported bridges under high-speed railway traffic, Eng. Struct. 72 (2014) 123–139.

[7] K. Nguyen, J. Goicolea, F. Galbadón, Comparison of dynamic effects of high-speed traffic load on ballasted track using a simplified two-dimensional and full three-dimensional model, Proc. Inst. Mech. Eng. F 228 (2) (2014) 128–142, http://dx.doi.org/10.1177/0954409712465710.

[8] K. Nguyen, C. Velarde, J.M. Goicolea, Analytical and simplified models for dynamic analysis of short skew bridges under moving loads, Adv. Struct. Eng. 22 (9) (2019) 2076–2088, http://dx.doi.org/10.1177/1369433219831481.

[9] A.K. Chopra, Dynamics of Structures: Theory and Applications to Earthquake Engineering, fourth ed., Prentice Hall, 2012.

[10] K.N. Gia, J.M. Goicolea, Vibration analysis of short skew bridges due to railway traffic using analytical and simplified models, Procedia Eng. 199 (2017) 3039–3046, http://dx.doi.org/10.1016/j.proeng.2017.09.407, X International Conference on Structural Dynamics, EURODYN 2017, URL https://www.sciencedirect.com/science/article/pii/S1877705817338997.

[11] K. Nguyen, J.M. Soria, I.M. Díaz, J.M. Goicolea, Exploring the potential of the semi-active inertial absorber in control resonant effects for short-to-medium span high-speed railway bridges, Struct. Infrast. Eng. (2023) 1–16, http://dx.doi.org/10.1080/15732479.2023.2292182.

[12] Evaluación Dinámica de Puentes de Ferrocarril; Seguridad e Interoperabilidad de Estructuras Existentes o Renovadas (EDINPF), https://www.upm.es/observatorio/vi/index.jsp?pageac=actividad.jsp&id_actividad=280737.

[13] Enhanced INterfaces and train categories FOR dynamic compatibility assessment of EUropean railway BRIDGEs (InBridge4EU), https://inbridge4eu.eu/.

[14] C. Gallegos-Calderón, J. Naranjo-Pérez, I.M. Díaz, J.M. Goicolea, Identification of a human-structure interaction model on an ultra-lightweight FRP footbridge, Appl. Sci. 11 (14) (2021) http://dx.doi.org/10.3390/app11146654, URL https://www.mdpi.com/2076-3417/11/14/6654.

[15] J. Naranjo-Pérez, C. Gallegos-Calderón, J.H. García-Palacios, I.M. Díaz, Vertical crowd–structure interaction modeling: Numerical and experimental assessment of a cable-stayed footbridge, J. Bridge Eng. 29 (4) (2024) 05024002, http://dx.doi.org/10.1061/JBENF2.BEENG-6388, URL https://ascelibrary.org/doi/abs/10.1061/JBENF2.BEENG-6388.

[16] DB InfraGO, ZBBD for investigations on dynamic compatibility between rolling stock and bridges, 2020, https://www.dbinfrago.com/resource/blob/12285556/72a2558484e386364a6829664794e34a/ZBBD-User-Manual_2020-02-14-data.pdf.