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RESULTS OF A COMPARATIVE DAMAGE DETECTION CASE STUDY

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Abstract: *A significant amount of attention has been devoted to rapid bridge testing in recent years at the Institute of Theoretical and Applied Mechanics. New methods, such as the Vehicle Scanning Method and Moving Impulse Load Testing, have been developed and/or tested on a scaled laboratory bridge model. This article summarizes all conducted tests, discusses the evaluation methods used, presents the results obtained, and explores possibilities for their improvement. Among the tested methods, the application of Moving Impulse Load (MIL) moving at slow speed, with an excitation frequency around the first natural frequency of the tested bridge, appears to be the most promising. Two passages of the MIL allow for an approximate estimation of the dominant natural frequencies, while repeated passages at small velocity increments provide an excellent means of detecting changes in structural stiffness.*

Keywords: Moving Impulse Load, Bridge Testing, Vehicle Scanning Method, Damage Detection

1. Introduction

Europe has approximately one million highway bridges (Casas, 2017), but most of this infrastructure was constructed in the 1960s and 1970s and is now facing increasing pressure due to traffic growth that was not anticipated at the time. Many bridges also lack proper maintenance, exposing users to greater risks, as highlighted by several unexpected collapses (e.g., the Morandi Bridge in Genoa), while owners face rising maintenance costs. This vulnerability necessitates effective and high-quality inspections and diagnostic methods (An, 2019). Although Bridge Health Monitoring is recommended, it is not cost-effective for smaller and medium-sized bridges today. In an effort to address this issue, several concepts have been examined at the Institute of Theoretical and Applied Mechanics in collaboration with our Taiwanese partners.

The first method investigated was the Vehicle Scanning Method (VSM) in the simple form of a moving spring mass. VSM (Wang, 2022) is theoretically efficient since it requires no transducers mounted on the bridge; instead, information about the bridge is gathered from transducers on the moving vehicle.

The second area of investigation focused on newly proposed MIL testing (Bayer, 2019), which was tested in various applications. A model test bridge, consisting of a simply supported steel beam that was progressively damaged, was used to assess the effectiveness of these methods in indicating and locating inflicted damage. While the tested methods have not yet guaranteed practical application, laboratory experiments have shown potential directions for further development to be pursued in the future. This case study serves as a record of experiences that may interest and inspire other researchers in the field.

2. Tested Bridge Model & Damage Cases

The tested structure was the rolled profile U 210x50x4 made from Steel S235 with a total length of 4005 mm and a span of 3980 mm. A line support was positioned 10 mm from one edge at the start, while two pin supports were located 15 mm from the opposite edge and 75 mm from the longitudinal axis of the beam.

An artificial defect was created on the beam at three-quarters of the span, as shown in Fig. 1, by making a 2 mm thick saw cut into the flanges, resulting in four damage cases, from D1 to D4.

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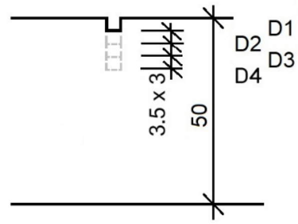

Fig. 1: Simulated damage (dimensions are in mm).

3. Tested Methods

3.1. Experimental Modal Analysis (EMA) Using an Impact Hammer

EMA was utilized as reference measurements to provide a comparison with a commonly applied method. Two Brüel&Kjaer accelerometers of type 4374 were attached to the beam (at the midpoint and at 0.625 of its span) and connected to a four-channel Nexus Conditioning Amplifier and a DEWE 43V measuring rack, which provided 24-bit resolution for data acquisition with 1 kHz sampling. The data was further processed in MATLAB. The beam was tapped with the impact hammer B&K 8202 at 20 measuring points arranged in two rows on both sides, spaced 0.25 m apart (9 points along each side and at the two positions of the accelerometers on the beam axis).

3.2. MIL Using a Cogwheel (CW)

MIL was generated by a rolling polygonal wheel weighing 506 g, moving at a constant velocity along the midline of the beam. Vibrations were measured with the same accelerometers used in EMA. At 0.475 of the span L, vertical displacement was also measured using the optoNCDT 1320 laser triangulation sensor. The CW traversed the beam at three different speeds: vh = 0.116, 0.127, and 0.134 m/s.

3.3. MIL Using a Cogwheel (CW) & Scanning Vehicle (SV)

This experiment was similar to the previous case, but no direct measurements were taken on the beam. Instead, vibrations were measured in a drive-by manner using the Brüel&Kjaer accelerometer (type 4374) attached to a vehicle traveling parallel to the CW, with the driving velocity adjusted in small increments.

3.4. Automated EMA using the CW

This test mirrored the previous one, but the CW and the SV moved at a very slow pace, with vehicles stopping briefly after each impact. Three accelerometers were utilized: two on the bridge and one on the vehicle. Modal parameters were evaluated from the free decay following each impact (Bayer, 2024).

3.5. Moving Spring Mass - Drive-by Identification

A vehicle weighing 956 g was equipped with a spring mass of 566 g featuring adjustable stiffness. One Brüel&Kjaer accelerometer (type 4374) was attached to the vehicle body, while another was affixed to the spring mass. An attempt was made to evaluate bridge frequencies according to Y.B. Yang's theory (Yang, 2004).

4. Achieved Results

4.1. Experimental Modal Analysis (EMA) Using an Impact Hammer

Tab. 1: Table 1: Experimentally Identified Natural Frequencies

D1 [Hz]	D2 [Hz]	D3 [Hz]	D4 [Hz]	Δ2 [%]	Δ3 [%]	Δ4 [%]
7,05	7,04	7,03	6,97	-0,27	-0,36	-1,18
27,48	27,39	27,35	27,20	-0,32	-0,46	-1,00
60,08	59,94	59,98	59,93	-0,23	-0,17	-0,25

This method successfully reflected all damage cases, documenting a gradual deterioration. Although the numerical evaluation of natural frequencies may not be conclusive in all instances (see Tab. 1), a comparison of frequency response functions at drive points effectively illustrated the gradual damage.

Estimated requirements of the in-situ experiment: 20 working hours (3 persons / 6 h ambient testing).

4.2. MIL Using a Cogwheel (CW)

This method provides multiple evaluation procedures for assessing structural changes:

4.2.1. Estimation of average peak frequencies (Damage Resolution (DR) comparable to 4.1, see Tab. 2)

Table 2: Experimentally Identified Peak Frequencies

D1 [Hz]	D2 [Hz]	D3 [Hz]	D4 [Hz]	Δ2 [%]	Δ3 [%]	Δ4 [%]
6,91	6,91	6,89	6,88	-0,06	-0,31	-0,52
27,21	27,11	27,03	27,02	-0,38	-0,67	-0,71
58,90	58,85	59,06	58,96	-0,09	0,27	0,11

4.2.2. Evaluation of spectral shifts (lower DR, subjective evaluation, lot of data to be processed)

4.2.3. Evaluation of harmonic peaks (lower DR, subjective evaluation, lot of data to be processed)

4.2.4. Evaluation of forced passage modes (revealed clear systematic changes on selected harmonic frequencies see Fig. 2)

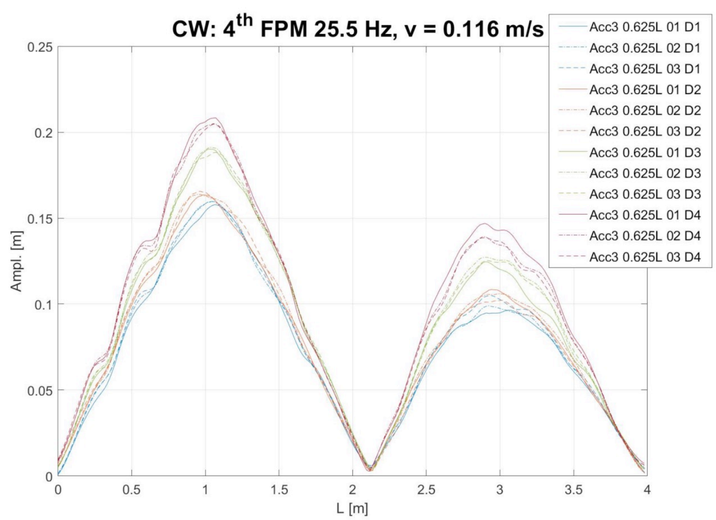

Fig. 2: Evaluated Forced Passage Modes at the 4th harmonic peak for all damage cases measured by accelerometer Acc3 at the position 0.625 of the span L for moving velocity 0.116 m/s.

4.2.5. Evaluation of pseudo-static Influence Lines can localize damage. However, the accuracy of measured displacements did not allow for reliable damage localization despite the resolution of the applied transducer being approximately five times lower than the maximum difference to be measured.

Estimated requirements of the in-situ experiment: 3 working hours (3 persons / 1 h) with resolution capability little lower or comparable with the 4.1 case). Shorter than EMA.

4.3. MIL Using a Cogwheel (CW) & Scanning Vehicle (SV)

This experiment is analogous to case 4.2. The advantage of this "drive-by" estimation comes at the cost of lower DR. Evaluations 4.2.1 – 4.2.4 could also be performed. The lower signal-to-noise ratio improves when distinctive bridge vibrations occur, such as in resonance conditions, allowing for clear differentiation between damage cases (see Fig.3). This evaluation can be conducted with even greater reliability within the framework of the 4.2 testing method.

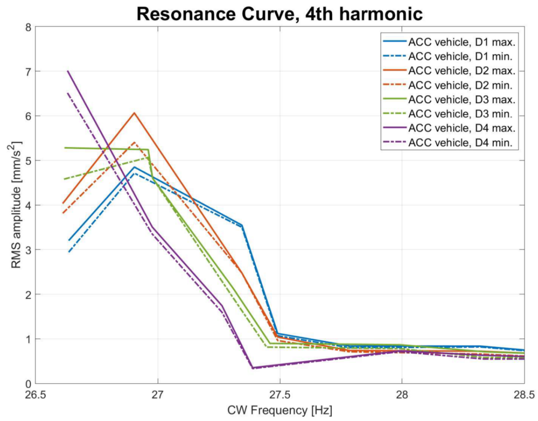

Fig. 3: Resonance curve evaluated for the fourth harmonic component using the CW&SV

4.4. Automated EMA using the CW

The experimental conditions were improvised with minimal effort and exhibited several weaknesses. Under these circumstances, it was possible to evaluate three mass-scaled modes with approximately 1% accuracy in frequency, although the quality of identified modes did not allow for reliable damage localization. But it is assumed that substantial quality improvements are possible.

4.5. Moving Spring Mass - Drive-by Identification

It was realized that evaluation based on Y.B. Yang's theory presents numerous practical limitations. The Drive-by Identification may be effective with instrumented railway wagon chassis; however, such a simplified model as tested is unlikely to be suitable for assessing bridge conditions.

5. Conclusions

From a practical applicability perspective, the most promising method is the MIL, which offers several usage options. It suggests shorter testing times for standard inspections (see 3.2/4.2) and provides more operational options for thorough condition assessments (automated operation - see 3.4/4.4; or precise evaluation of resonance peaks - see 3.3/4.3). A single MIL-generating vehicle can be used to repeatedly check many bridges. This proposed testing technique could offer an efficient and economical tool for commissioning tests, condition assessments, and health monitoring of smaller and medium bridges.

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