Experimental Campaign on the Application of Fast Falling Weight Deflectometer for Possible Rapid Bridge Condition Monitoring

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Abstract. The following paper describes the possible applications of the Fast Falling Weight Deflectometer (Fast-FWD) as a tool for quantitatively characterizing the performance and condition of bridges by measuring the stiffness of the deck and embankment. The FWD is already widely used by transportation agencies for pavement evaluation programs and airfield pavement testing campaigns. This paper reports the testing campaign conducted on eight bridges in which the efficacy of using a Fast-FWD, a controlled excitation device for impact dynamic testing, on short to medium span reinforced concrete bridges.

There are many testing methods available, capable of monitoring and evaluating the performance and condition of bridges. Full scale testing consists of static load and dynamic testing methods using either controlled or uncontrolled dynamic excitation. Although each method has advantages and disadvantages in terms of the experimental campaign, logistical purposes and data analysis are also time consuming. This research establishes that the testing campaign, involving the measurement of local deflections of bridge structures to obtain stiffness values, resulted in rapid, accurate, and cost-effective assessments with minimal impact on traffic flow, providing a valuable alternative to traditional testing methods. Further validation and integration efforts are necessary, to fully exploit the potential of Fast-FWD in bridge assessment practices.

Keywords: Fast Falling Weight Deflectometer · non-destructive test · bridge monitoring · reinforced concrete bridges

1 Introduction

Bridge monitoring is a crucial preventive action for the safety of infrastructure. Deterioration due to aging, material degradation, poor maintenance, and also increasing traffic volume can induce a significant modification in the static and dynamic response of the infrastructure. In some cases, bridges have already exceeded their service life [1]. The methods used to investigate bridge vulnerability aim to predict potential collapses. Factors such as fatigue, corrosion of reinforcement, and aging are critical to evaluate the residual life span of each bridge structure [2]. Visual inspections [3], while simple, low-cost,

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and commonly used, may not be always totally adequate to detect impending collapse phenomena. On the other hand, monitoring through dynamic response identification is a more complex approach that demands substantial computational resources.

The collapse of the Morandi Bridge in Italy in 2018, shown in Fig. 1, which resulted in international attention and prompted a significant call for improved monitoring of road infrastructures, triggered widespread attention to the formulation of specific guidelines by the Italian Ministry of Infrastructure and Transportations [4, 5]. These guidelines were developed to outline comprehensive monitoring procedures aimed at preventing similar tragedies from occurring in the future.



Fig. 1. Morandi Bridge collapse, Genova, 2018 (source commons.wikimedia).

In this paper, we analyze the development of a non-destructive, rapid, repeatable over time, and highly efficient procedure (low cost and high precision) using the Fast Falling Weight Deflectometer (Fast-FWD) on road reinforced concrete bridges. The FWD, classified by the testing methods used, falls into the category of equipment known as Impact Load Devices (ILD), which evaluate the reactions of a structure in various areas of transport. Typically used in road pavements and airport runways, by applying an impulsive load through the dropping of a mass with known characteristics. The utilization of FWD for assessing stiffness values of pavement structures [6] was introduced in the late 1970s, allowing the evaluation of degradation curves and related maintenance actions.

The instrument records, through specific sensors (geophones), the deflection, understood as temporary deformation in the vertical direction, of the investigated surface. The particular arrangement of the geophones relative to the center of the mass drop

allows for the detection of deflection at various points on the surface at varying distances from the load center, thus enabling the evaluation of a deflection basin. Analysis of the shape and characteristics of the deflection basin allows, through accurate and complex back-calculation models, the determination of the characteristics of the underlying layers including material stiffness. In the literature, there are cases in which the FWD for assessing bridge condition was used. In 1996, a study conducted in Virginia, USA, utilized the FWD to measure deflections on the decks of two bridges [7]. This application likely aimed to assess the structural integrity and performance of the bridges by evaluating their deflection behavior under load. Another case study, conducted in 2001, involved measuring the natural frequency of a bridge using the FWD [8]. This study compared the obtained natural frequencies with previous test results to identify any potential damage or changes in the bridge's structural properties over time. Additionally, there's a suggestion in the literature to employ large impulse sources like the FWD for locating natural frequencies during preliminary vibrating testing of bridges [9]. This indicates a potential application of FWD in the initial assessment stages of bridges to identify their dynamic characteristics.

In 2019, a study was conducted in Sardinia, Italy, focusing on a short single-span bridge exhibiting visible structural damage. Subsequently, in 2021, another study was carried out on a multiple-span bridge in the same region. Both studies employed Fast-FWD technology to assess bridge stiffness, aiming to provide engineers with valuable insights into bridge performance and conditions [10, 11].

This research aims to apply this technology, which is well-established in the field of rigid, semi-rigid, and flexible pavements, to evaluate bridge stiffness across various types of reinforced concrete bridges divided into single-span and multiple-span bridges. There is a need to gather data to gain a better understanding of the potential application of FWD in bridge monitoring, aiming to rapidly assess the degradation status of bridges and viaducts. The paper is divided into five sections. Section 2 elaborates on the proposed methodology, while Sect. 3 demonstrates its practical implementation through a case study. Section 4 presents data analysis based on the obtained results. Lastly, Sect. 5 concludes this study, providing insights into the importance of FWD applications in Structural Health Monitoring (SHM) of bridges, and their potential influence on infrastructure monitoring practices.

2 Methods

2.1 Falling Weight Deflectometer

The Fast-FWD, shown in Fig. 2, is a device used to assess the bearing capacity of pavements, roads, and airport runways. It's particularly useful for evaluating the stiffness and resilience of pavement materials and identifying any structural issues. The operation of the FWD relies on the principle of applying a dynamic load to the pavement through a falling weight. When the weight drops onto the pavement, it creates a localized deformation. Sensors mounted on the deflector measure the pavement's deflection caused by the load. This deflection is directly related to the material stiffness and its ability to support the load [12]. In other words, the stiffer the pavement, the less deflection there will be under the load. The testing process typically involves dropping a known weight from a

specific height onto the surface of the pavement under examination. Geophones measure the speed and extent of the pavement deformation during contact with the falling weight and subsequent rebound.

The information collected by the FWD is used to calculate important parameters such as the pavement's modulus of elasticity, bearing capacity, presence of structural defects, and the depth of the supporting material. These data are crucial for the design and maintenance of road infrastructure, as they help identify pavements that require repairs or replacements.



Fig. 2. Fast-Falling Weight Deflectometer, used in the testing campaign.

In this paper, Fast-FWD is analyzed as a non-destructive and quick test procedure to evaluate the efficiency of short to medium span bridges. The Fast-FWD is an instrument that can produce a broadband dynamic force up to an impact value of 120 KN [13]: the impact is constant and replicable, providing accurate action measures of bridge stiffness in a truly short period (30 ms). The testing campaign involved the investigation of 8 concrete bridges. Figure 3 shows the Fast-FWD in action during bridge monitoring.

Figure 4 displays a typical deflection basin recorded by the geophones following the application of an impulsive load. The profile of deflection is shaped by the characteristics inherent to each layer of the pavement, as well as the magnitude and frequency of the loading [6]. The maximum deflection occurs at the loading point, as measured by the D_0 geophone. In total, 12 geophones were employed throughout the testing campaign.

2.2 Data Acquisition and Analysis

In the evaluation performance of road or airport pavements performance, Fast-FWD results play a crucial role. These assessments often hinge on Deflection Basin Parameters (DBPs), commonly referred to as the "Basin Index" (BI). These indices, namely the Surface Curvature Index (SCI), Base Damage Index (BDI), and Deep Layer Index (DCI), are derived from the maximum deflection values measured at designated distances from



Fig. 3. Fast-FWD performing bridge testing campaign, bridge on road SP 87.

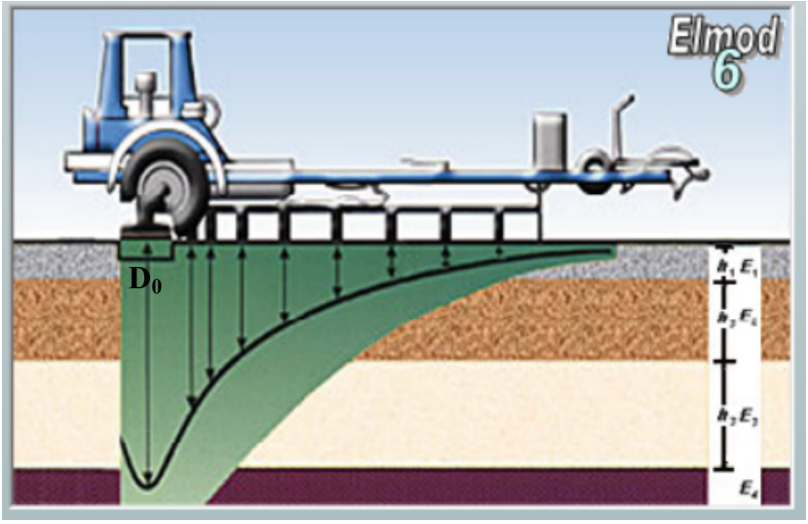

Fig. 4. Deflection Basin and schematic geophones position (source Dynatest operation manual).

the loading mass (expressed in millimeters). They offer valuable insights into the condition of the underlying pavement layers, aiding in the identification of potential issues and guiding maintenance decisions.

The calculation of these indices involves specific formulas:

Surface Curvature Index (SCI):

$$SCI = D_0 - D_{300} \tag{1}$$

Base Damage Index (BDI):

$$BDI = D_0 - D_{600} \tag{2}$$

Deep Layer Index (DCI):

$$DCI = D_{900} - D_{1200} \tag{3}$$

where D_0, D_{300}, D_{600}, D_{900}, and D_{1200} represent the maximum deflection values at respective distances in mm from the loading mass.

These indices serve as quantitative indicators, allowing for a comprehensive assessment of pavement conditions and facilitating informed decision-making regarding maintenance and rehabilitation strategies.

In this paper, the methodology employed to analyze stiffness (K), obtained from the ratio between the maximum applied load (F) and the maximum axial deflection (D_0), which served as a direct measure of local stiffness [10, 11]:

$$K = F/D_0 \tag{4}$$

The tests are conducted at fixed station points strategically chosen to thoroughly assess both the deck, the approach ramp of the bridge, the abutment, and also in correspondence of the beams. The alignment of the support structures of the deck is carefully selected to accurately evaluate the actual constraints experienced. Testing on the approach ramp provides a valuable basis for comparing results obtained from the pavement, without the confounding effects of the bridge deck. This approach allows for the identification of an appropriate survey grid for each specific bridge.

Each station point requires testing in both directions to determine the orientation of the geophone bars effectively. Conducting at least three measurements at each station point, with varying degrees of falling load, is crucial for discerning the mechanical properties of the bridge. Deflection data should be cross-referenced with pavement information gathered through methods such as core drilling and visual inspections with micro-cameras, aiding in the detection and assessment of pavement layer types and thicknesses.

3 Case Study

The testing campaign was conducted, on eight reinforced concrete bridges located in the southern region of Sardinia, Italy. The testing campaign took place over two days. Figure 5 illustrates the precise location of the tested bridges. During the testing campaign, a visual investigation of the structural components was performed and a report was generated detailing any observed defects.

Table 1 provides information regarding the tested bridges. The first column specifies the type of bridge, followed by geometric details such as total length and width. Additionally, the table includes the name of the road to which each bridge belongs, with "SP" denoting a provincial road followed by a number. The initial four bridges feature multiple spans, with lengths ranging from 80 to 98 m, whereas the remaining four are

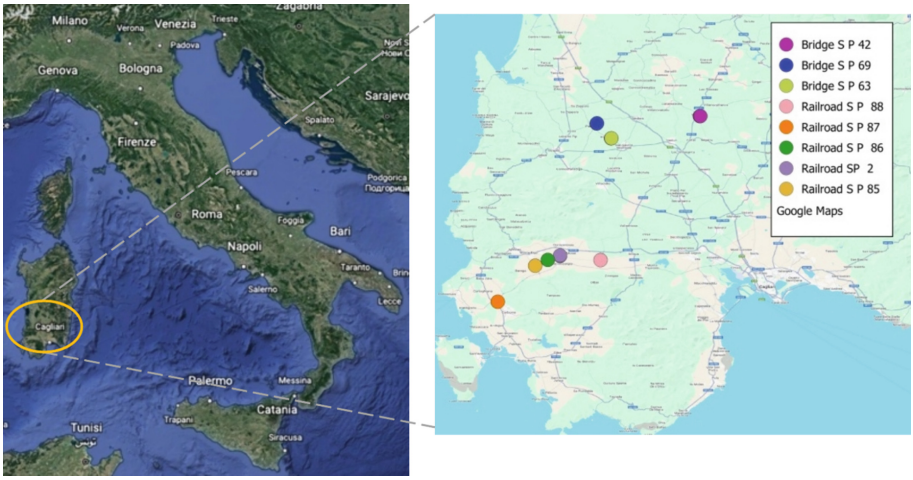

Fig. 5. Position of the eight tested bridges (source Google Maps and QGis).

Table 1. Geometric characteristics and locations of the tested bridges.

Bridge Type	Length (m)	Width (m)	Additional information
n°1. Multiple span beam bridge	80	6.5	Three span bridge road SP 63
n° 2. Multiple span beam bridge	80	5	Three span bridge road SP 69
n°3. Multiple span beam bridge	98	7	Five span bridge road SP 42
n°4. Multiple span beam bridge	90	8	Five span bridge road SP 87
n°5. Single span Arch bridge	11	7	Railway overpass arch bridge road SP 86
n°6. Single span Arch bridge	9	7	Railway overpass arch bridge road SP 85
n°7. Single span beam bridge	11	9	Railway overpass bridge road SP 2
n°8. Single span beam bridge	16.5	9	Railway overpass bridge road SP 88

single span railway overpass bridges. Gathering and comparing data from bridges with different structures is crucial.

Before the testing campaign started, a schematic grid of testing points was established for each bridge, considering the geometrical structure. An example of this can be seen in Fig. 6 regarding bridge n°2. Tests were conducted alternatively on both lanes without the need to close the bridge. Where possible, testing was also performed in the center line. However, conducting tests in the centerline sometimes necessitated the suspension of traffic, which was not always possible due to the volume of traffic. The difference in color of the testing points reported in Fig. 6 considers different testing elements. Tests conducted on the deck are marked in purple, those in correspondence with the beams in

red, and those on the approach ramp in green, for a total of 45 testing points. For each testing point, three load impulses were applied with increasing vertical stress levels of 900, 1200, and 1600 kPa. Also, a view of bridge n°2 can be seen in Fig. 7.

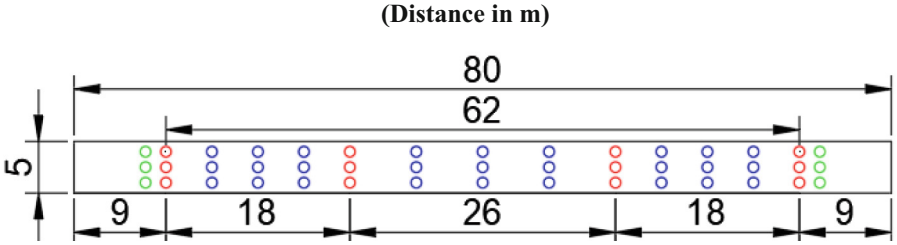

Fig. 6. Schematic positioning of testing points on Bridge n°2 along SP 69 road (Cad.Drawing)



Fig. 7. View of bridge n°2 on road SP 69 (source Google Earth).

Table 2 reports the number of testing points conducted on each bridge and the number of alignments performed, specifying the locations of the alignments, encompassing both lanes and, when possible, on the centerline.

4 Data Analysis

A summary of the stiffness values for the first four multiple span bridges is reported in Table 3. Reporting both average values and standard deviation for each of the tested elements. Stiffness values were calculated using equation n°4, where F represents the maximum applied load of 1600 kPa and D_0 denotes the maximum deflection measured in μm.

Table 2. Testing procedure information.

Bridge Type	Tested points N°	Alignments N°	Position
n°1.Multiple span beam bridge	45	3	2 lanes and centerline
n° 2. Multiple span beam bridge	45	3	2 lanes and centerline
n°3. Multiple span beam bridge	81	3	2 lanes and centerline
n°4. Multiple span beam bridge	46	2	2 lanes
n°5. Single span Arch bridge	14	2	2 lanes
n°6. Single span Arch bridge	14	2	2 lanes
n°7. Single span beam bridge	14	2	2 lanes
n°8. Single span beam bridge	15	2	2 lanes

Table 3. Stiffness (K) values for each tested element of multiple span bridge.

Bridge	Deck mean K (GN/m)	Deck STD K (GN/m)	Beam mean K (GN/m)	Beam STD K (GN/m)	Approach Ramp mean K (GN/m)	Approach Ramp STD K (GN/m)
n°1	0.41	0.08	0.61	0.38	0.26	0.03
n° 2	0.32	0.07	0.61	0.28	0.24	0.06
n°3	0.46	0.25	1.13	0.60	0.09	0.02
n°4	0.33	0.10	0.67	0.28	0.30	0.04

To better understand the variation of the mean stiffness values, they have been graphically depicted for each element of the four bridges, see Fig. 8. Upon initial examination, it becomes apparent that the mean stiffness values for the beams are higher compared to those of the deck and approach ramp, which exhibit lower stiffness.

Also to better understand the variability of the data the ratio between the standard deviation and the mean values was calculated and is reported in Table 4.

The variability in data is significantly higher for the beams in comparison to the deck, whereas the approach ramp displays the least variability along with the lowest stiffness values.

A similar analysis was conducted for the remaining four bridges detailed in Table 5, with the first two being arch railway overpass bridges and the remaining two being single span bridges.

To better analyze the trend of mean stiffness values, for each element of the four bridges they have been depicted on a chart in Fig. 9.

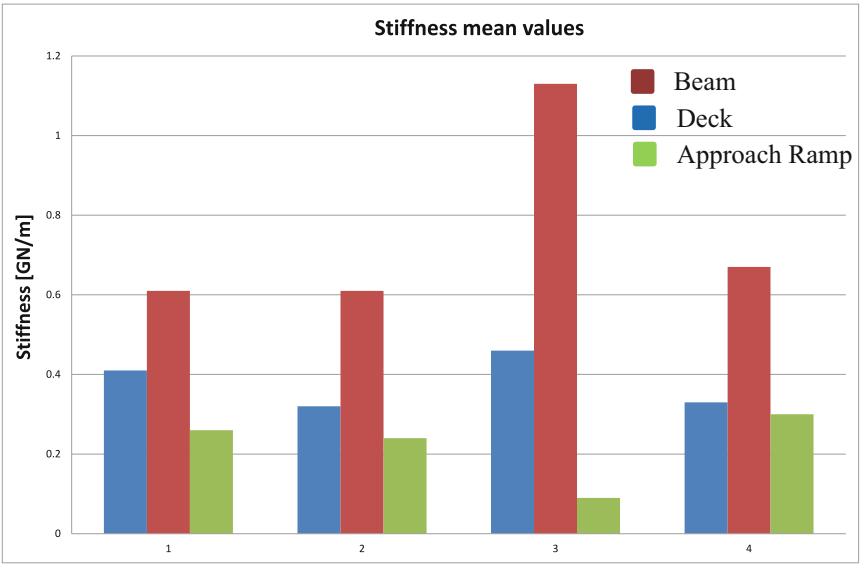

Fig. 8. Average stiffness values for each element of the four tested multiple span bridges.

Table 4. Variability of the data.

Bridge	Deck STD/mean K (GN/m)	Beam STD/mean K (GN/m)	Ramp STD/mean K (GN/m)
n°1	0.19	0.63	0.13
n° 2	0.21	0.45	0.26
n°3	0.55	0.53	0.27
n°4	0.32	0.42	0.14

It can be seen how the higher values of stiffness are those of the abutment of the single span bridges while the arch bridges have much lower values. Overall mean values for each of the tested elements are higher in the single span bridges. In Table 6 the variability of the data is reported and compared. In most cases, it can be seen that for each element the variability is quite similar in the four bridges.

Comparing stiffness variability between multiple span bridges and single span ones reveals that multiple span bridges often display significantly greater variability in data.

Attention was focused on the stiffness values of single span bridges, analyzing the deck values and the exact testing positions marked in purple. The following figures: Figs. 10, 11, 12, and 13, illustrate the test positions on the deck along with the corresponding stiffness values reported in GN/m.

Table 5. Stiffness (K) values for each tested arch and single span bridge.

Bridge	Deck mean K (GN/m)	Deck STD K (GN/m)	Abutment mean K (GN/m)	Abutment STD K (GN/m)	Approach Ramp mean K (GN/m)	Approach Ramp STD K (GN/m)
n°5	0.27	0.09	0.20	0.04	0.17	0.03
n°6	0.23	0.04	0.21	0.04	0.39	0.07
n°7	0.33	0.08	1.08	0.23	0.37	0.07
n°8	0.37	0.04	1.32	0.33	0.54	0.22

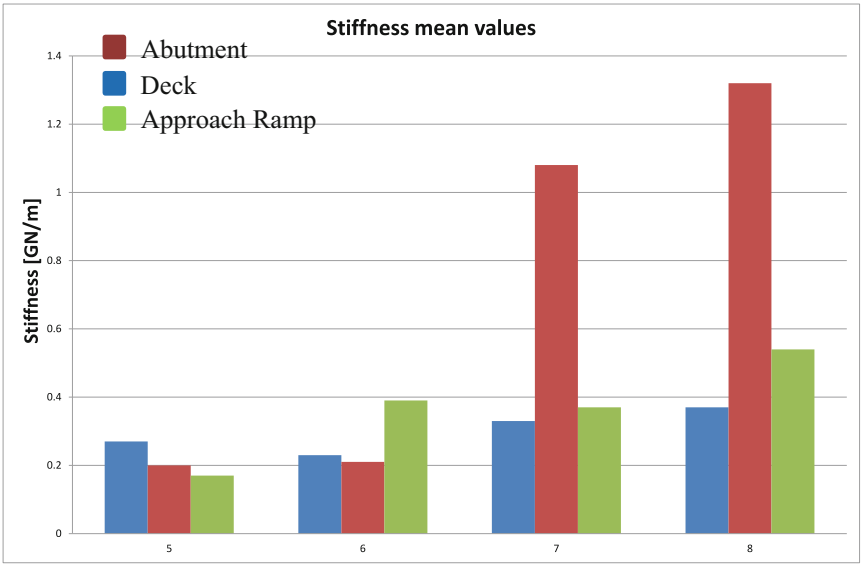

Fig. 9. Average stiffness values for each element of the four bridges.

Table 7 summarizes the values of stiffness measured on the bridge deck of the remaining four tested bridges.

Table 6. Variability of the data.

Bridge	Deck STD/mean K (GN/m)	Beam STD/mean K (GN/m)	Ramp STD/mean K (GN/m)
n°5	0.33	0.19	0.19
n°6	0.19	0.20	0.19
n°7	0.24	0.21	0.19
n°8	0.10	0.25	0.42

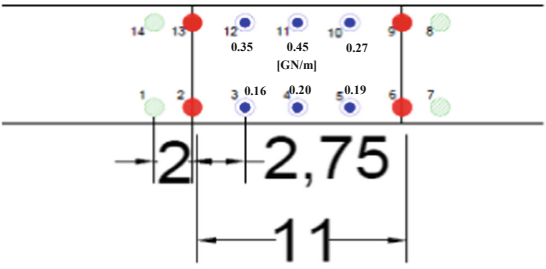

Fig. 10. Single span arch bridge n°5 (Cad Drawing).

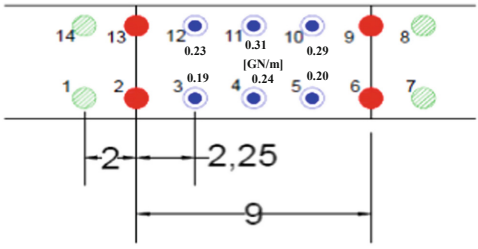

Fig. 11. Single span arch bridge n°6 (Cad Drawing).

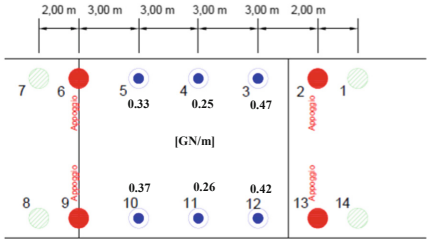

Fig. 12. Single span bridge n°7 (Cad Drawing).

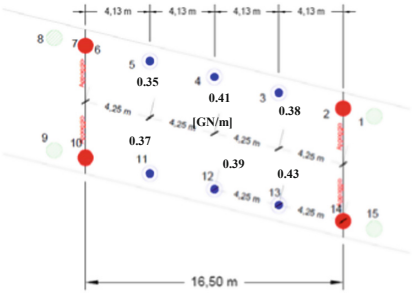

Fig. 13. Single span bridge n°8 (Cad Drawing).

Table 7. Stiffness values of the deck by position.

Bridge	Deck Left K (GN/m)	Deck Center K (GN/m)	Deck Right K (GN/m)
n°5	0.16	0.20	0.19
	0.35	0.45	0.27
n°6	0.19	0.24	0.20
	0.23	0.31	0.29
n°7	0.33	0.25	0.47
	0.37	0.26	0.42
n°8	0.35	0.41	0.38
	0.37	0.39	0.43

It is feasible to assess how the two types of bridges respond differently to the applied load impulse. The arch bridges at the center of the deck demonstrates higher stiffness values if compared to those on the left and right sides. Conversely, this consistent trend is not observed in the single span beam bridge; furthermore, an opposite behavior emerges with higher values noted on the left and right sides of the deck when compared with the center.

5 Conclusions

In this preliminary analysis of the obtained data, it can be concluded that the utilization of Fast-FWD for screening existing reinforced concrete bridges offers a promising method for quickly evaluating their vulnerability. Its primary advantage lies in the minimal disruption it causes and the brief duration needed to gather both static and dynamic structural data. This suggests the potential use of Fast-FWD tests for regular monitoring of bridges and viaducts. Monitoring changes in parameters such as deflection basin and

stiffness over time provides valuable insights into how aging or other factors affect the structures.

The data analysis comparing multiple span bridges to single span ones clearly shows that multiple span bridges display greater variability in stiffness values across each tested element. Specifically, multiple span bridges exhibit higher stiffness values in the beams, and expected structural response, while the deck and approach ramp indicate lower values, with the approach ramp displaying the lowest values and minimal variability. Hence, to gain deeper insights into this behavior, it's essential to test as wide a range of bridge types as possible, underscoring the importance of case studies.

However, single span bridges display different behaviors. In the case of the two single span arch bridges, stiffness values are higher in the central portion of the deck, while they are lower on the left and right sides. Conversely, in the two single span beam bridges, one bridge exhibits larger stiffness values at the left and right sides and smaller values in the central portion of the span, while the other bridge does not demonstrate this type of behavior.

Further examination of the acquired data is imperative to gain a deeper understanding of the behavior of the tested bridges. This involves analyzing not only the obtained stiffness values but also assessing linearity behavior to identify any notable structural degradation. Due to the complexity of bridge structure behavior, it's crucial to broaden our scope by conducting multiple testing campaigns across a diverse range of bridge types. By doing so, we can ensure a more thorough understanding of bridge performance under various conditions.

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References

1. Pregnolato, M.: Bridge safety is not for granted a novel approach to bridge management. Eng. Struct. **196**, 109193 (2019)
2. Santarsiero, G., Masi, A., Picciano, V.: Durability of Gerber Saddles in RC Bridges: analyses and applications (Musmeci Bridge, Italy). Infrastructures (2021)
3. Stochino, F., Fadda, M.L., Mistretta, F.: Low cost condition assessment method for existing 375 RC bridges. Eng. Fail. Anal. **86**(2018), 56–71 (2018)
4. Guidelines on Risk Classification and Management, Safety Assessment and Monitoring of Existing Bridges; Ministry of Infrastructure, CSLP: Rome, Italy (2020)
5. Ministry of Infrastructure Decree no. 578 del 17/12/2020. Enforcement of the Guidelines on risk classification and management, safety assessment and monitoring of existing bridges (2020)
6. Bamrungwong, C.: Development of a Falling Weight Deflectometer (FWD) for Evaluating the Pavement Conditions. Asian Transportation Research Society, Bangkok Thailand (2009)

7. Hoadley, P.W., Gomez, J.P.: Structural Stiffness Identification of Bridge Superstructures: Final Report; Virginia Transportation Research Council: Charlottesville, VA, USA (1996)
8. Catbas, F.N., Ciloglu, K., Celebioglu, A., Popovics, J.S., Aktan, A.E.: Fleet health monitoring of large populations: aged concrete Tbeam bridges in Pennsylvania. In: Proceedings of the 6th Annual Int'l Symposium on NDE for Health Monitoring and Diagnostics, Newport Beach, CA, USA (2001)
9. Turnage, R.S., Baber, T.: Field Testing of the Wolf Creek Curved Girder Bridge: Part I: Vibration Tests; Virginia Transportation Research Council: Charlottesville. VA, USA (2009)
10. Coni, M., Mistretta, F., Stochino, F., Rombi, J., Sassu, M., Puppio, M. L., Fast Falling Weight Deflectometer Method for Condition Assessment of RC Bridges, Applied Sciences, Vol. 11, No. 4. (2021)
11. Puppio, M. L., Mistretta, F., Coni, M., Sassu, M., Non-destructive and effective bridge monitoring through fast-falling weight deflectometer, IABSE Congress Ghent 2021 - Structural Engineering for Future Societal Needs (2021)
12. Punthutaecha, K., Manokhoon, K., Kongkitkul, W., Youwai, S., Development of Falling Weight Deflectometer (FWD) for Evaluating the Pavement Conditions, Research Report 2008 Project No: A-08/ 001 (2009)
13. Dynatest FastFWD Test Systems manual, Dynatest International A/S (2015)