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REMOTE TESTING AND ASSESSMENT OF DIFFERENT TYPES OF BRIDGES USING ADVANCED EVALUATION METHODS

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Abstract

This paper presents the procedure for remote testing of various categories of bridges, incorporating both static and dynamic assessment methodologies. The investigated structures include different types of bridges categorized by the structural system and materials, as well as different categories of bridges according to their usage. Therefore, the study incorporates a cable-stayed steel pedestrian bridge, a simply supported steel girder railway bridge and a prestressed reinforced concrete road bridge. The objective of the testing was to evaluate the structural performance, safety, and long-term serviceability of these diverse bridge types under varying load conditions. For the testing phase, an advanced radar technique called microwave interferometry is employed. Using a high-precision interferometric radar system to remotely monitor deflection patterns, any subtle displacements with millimetre-level accuracy were detected. Additionally, accelerometer devices were employed to record the resulting accelerations and vibration patterns, enabling a detailed analysis of the structural behaviour under dynamic loads and confirming the accuracy of the interferometric remote testing procedure. The combination of static and dynamic testing allowed for a thorough evaluation of the bridges' stiffness, damping characteristics, and overall structural integrity. The findings highlight key insights into the current condition and performance of the various types of bridges. Overall, the study emphasizes the necessity of integrating static and dynamic testing methodologies for accurate structural assessment, especially in complex traffic networks. The findings provide a strong basis for informed decision-making regarding maintenance strategies, ensuring the continued safety and serviceability of these critical infrastructures. Regular monitoring and timely intervention based on these insights are essential to extending the lifespan and reliability of the bridges.

Keywords: bridges, testing, remote, assessment, interferometry, static, dynamic.

1. Introduction

Bridges are critical components of modern infrastructure, providing essential connections for transportation and commerce. As these structures age and become subjected to increasing loads and environmental challenges, their safety and performance must be regularly evaluated. The importance of effective assessment methodologies cannot be overstated, particularly given the possible consequences of structural failures, which can lead to significant economic loss and pose threats to public safety.

Beginning with the design, continuing onto the construction phase and concluding with the exploitation of the bridge structures, obtaining the correct and up-to-date data is crucial for assessment of their

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behaviour. From a simple routine maintenance to check the serviceability of the bridge, through visual inspection to assess the condition of the bridge, the thorough inspections require detailed engineering investigation using various testing methods and theoretical structural analysis. The technology has advanced greatly, thus the use of unmanned aerial systems (UAS) has already been widely accepted and implemented as a method for obtaining key information on structural condition of bridges [1-7]. Moreover, machine learning (ML), as part of the rapidly advancing artificial intelligence (AI) application in engineering, through its deep learning models provides state of the art results to problems that are initially considered to be intuitively solved by humans [8]. Using the benefits of highly developed computer vision solutions, new frameworks for monitoring of bridges can be implemented as well [9].

In recent years, advancements in testing technologies have opened new avenues for the remote evaluation of bridges, allowing engineers to gather detailed information about structural performance without the need for intrusive measures. Therefore, techniques such as digital image correlation (DIC), interferometer radar, LiDAR systems, total stations etc. have been successfully incorporated into the monitoring plans for bridges. Garnica et al. [10] have reviewed the various sensors and measuring techniques that are applicable to load testing of concrete bridges and found that deflections can be accurately measured with an interferometric radar and that non-contact techniques are the better choice for bridges that are difficult to access. Employing microwave interferometry, an advanced radar technique, deflection patterns can be monitored to achieve millimetre-level accuracy in detecting subtle displacements. The interferometric radar's most significant advantage over other remote sensing techniques is its high precision evaluated in laboratory environments [11, 12]. It can be used as a single radar measuring the vertical displacements of the bridge structure with high frequency and accuracy, or different configurations using two or more radars can be implemented in order to tackle the monitoring problems associated with more complicated geometries or bridge types [13, 14].

This paper presents a comprehensive procedure for remote testing of various categories of bridges, incorporating both static and dynamic assessment methodologies and using interferometric radar in all case studies. The study investigates a range of bridge types, specifically focusing on a cable-stayed steel pedestrian bridge, a simply supported steel girder railway bridge, and a prestressed reinforced concrete road bridge. This diversity in structural systems and materials underscores the complexity of bridge assessment and the necessity for tailored evaluation techniques. By emphasizing the necessity of comprehensive testing methodologies, it is aimed at supporting the development of effective maintenance strategies that safeguard public safety and enhance the serviceability of bridges.

2. Bridge inspection overview

2.1. Methodology for bridge monitoring and assessment

This section outlines the systematic approaches used to monitor and assess the health of bridges. The methodology typically involves four key components: monitoring techniques, data acquisition, structural assessment and evaluation methods.

Bridge monitoring involves the use of a wide range of tools and techniques to investigate structural performance. These can involve visual inspection, structural health monitoring (SHM) systems, non-destructive tests (NDT), remote monitoring systems and smart materials and sensors. The visual inspection is usually performed by experienced engineers and it can result in detection of cracks, spalling of concrete or corrosion of the steel and reinforcement. SHM systems are more advanced tools for monitoring of bridge structures and they incorporate automated systems with sensors, data acquisition units and analytical software solutions. They can be differentiated via the character of the monitoring as static or dynamic and they can also provide monitoring data in long-term and in real-time. NDTs are one of the most frequently used techniques for assessing the material properties of the bridge structures as they provide very useful data without causing damage to the structural elements. Finally, the remote monitoring systems and smart materials and sensors are the state-of-the-art

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technologies for structural monitoring that are used for data obtaining without the need of physical proximity of the investigated structure.

After the suitable inspection and monitoring method is selected, accurate data acquisition and efficient data management are crucial for effective bridge monitoring. The data acquisition procedure consists of proper sensor placement and calibration, the possibility of real-time data acquisition, robust data storage and management systems and big data and analytics techniques to process large volumes of monitoring data as well as identify patterns, anomalies and predict failures.

After monitoring data is collected, structural assessment and modelling help interpret the data. To provide an accurate interpretation of the physical engineering parameters from the monitoring phase, a robust finite element modelling (FEM) for simulation of the bridge behaviour under various load conditions is required. Numerical modelling can also be employed to perform model updating using the monitoring data to improve accuracy. The dynamics principles can therefore be applied for identifying changes in modal properties, while the mechanics principles and suitable material behaviour properties can be utilized for detecting excessive deformation and cracking. The most advanced ML and AI techniques such as the deep learning are more frequently used for supervised and unsupervised learning for anomaly detection and damage classification and prediction.

The final step involves evaluating the health of the bridge and assessing associated risks. Thus, development of a quantifiable index to represent the overall condition of the bridge which combines data from various monitoring sources is required. Probabilistic methods are applied to evaluate the likelihood of failure under specific conditions with focus on load-carrying capacity, fatigue, and environmental factors. These measures result in integration of monitoring and assessment data into a overall management system which facilitates prioritization of maintenance, repair, or replacement activities.

Bridge inspection frameworks in developed countries emphasize routine inspections, advanced technologies, and centralized data systems for managing bridge infrastructure. They mandate regular inspections to assess structural integrity and safety. Generally, the regular inspections are conducted more frequently to visually assess all accessible parts of the structure [15-19]. Additionally, thorough inspections are performed, involving detailed visual checks and load-bearing capacity evaluations [20]. Also, many of the bridge inspection standards include post-event inspections following extreme weather or seismic events that involve more comprehensive assessment of the structure. While commonalities exist, variations in environmental conditions, traffic demands, and regulatory standards have shaped unique approaches in each region, Table 1. Continuous innovation, including the adoption of AI, digital twins, and IoT, will further enhance these frameworks, enabling proactive maintenance and improved safety.

Table 1. Comparison of bridge inspection frameworks in developed countries

Country	Inspection frequency		Technologies used	Unique feature
	Routine	Other		
Australia	2-5 yrs	Risk-based	IoT sensors, NDT	Multi-level inspection hierarchy
Canada	Not defined	Post-event	GPR, LiDAR, SHM	Focus on extreme weather resilience
UK	2 yrs	6 yrs (risk-based)	Drones, condition indices	Risk-based inspection prioritization
USA	2 yrs	Risk-based	NDT, drones, SHM, ML	Centralized NBI for data management
Japan	5 yrs	Post-disaster	SHM	Advanced SHM adoption for seismic resilience
Germany	1 yr	6 yrs	Drones, SHM	Sustainable bridge management

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Regarding the advanced technologies that enhance the bridge inspection procedures, several authors have proposed suitable adjustments of the existing frameworks [21-23]. Others have detected the need for evaluating the remote sensing technologies for the next generation bridge inspection methodologies. They noted that monitoring the condition of a bridge using remote sensors can eliminate the need for traffic disruption or total lane closure because remote sensors do not come in direct contact with the structure [24].

2.2. Instrumentation

Laser sensors are a possible non-contact technique for monitoring large structures such as bridges. Consequently, a remote microwave sensor able to provide displacement measurements with sub-millimeter accuracy and a sampling rate high enough to track the transient movements of an architectural structure was developed [25]. The microwave interferometric radar measures the static deflections of several points on a large structure, as well as vibrations to identify resonant frequencies and mode shapes. The IBIS-FS interferometric radar is a ground-based remote sensing system widely used for monitoring the stability and deformation of structures such as bridges, dams, and buildings. It employs radar interferometry to measure sub-millimetre displacements over large areas in real time, offering a non-contact, high-precision solution for structural health monitoring (SHM). The system uses electromagnetic waves to detect changes in the structure's surface, providing continuous data without requiring physical sensors or extensive setup, Fig. 1. Its portability and ability to operate under diverse environmental conditions make it particularly valuable for both short-term assessments and long-term monitoring applications. It is therefore the main instrument used for this investigation, applied on all of the varying case study structures.

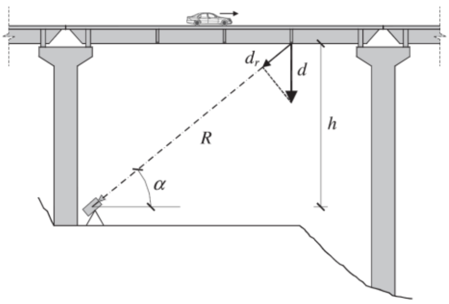

Figure 1. Typical setup of interferometric radar IBIS-FS for bridge static and dynamic measurement [26].

Simultaneously, accelerometers were used to record the resulting accelerations and vibration patterns, facilitating a thorough analysis of structural behaviour under dynamic loading conditions. This dual approach enables a comprehensive assessment of important parameters such as stiffness, damping characteristics, and overall integrity of the bridges.

During one of the case studies, UAS inspection was also conducted. For that purpose, a sophisticated drone technology was used. The DJI Phantom 4 Pro V2.0 is an advanced unmanned aerial vehicle (UAV) designed for professional applications such as structural inspections of structures and bridges [27]. Its 1-inch 20-megapixel CMOS camera ensures high-resolution imagery and 4K video recording at 60 fps, while the mechanical shutter eliminates rolling shutter distortion, crucial for accurately capturing structural details during fast movements. The drone's intelligent battery supports a flight time of up to 30 minutes, reducing the need for frequent landings and enabling efficient coverage of large structures. User-friendly controls and automated flight modes, make the Phantom 4 Pro V2.0 accessible to both novice and experienced operators. The included controller connects with mobile phone or tablet, ensuring clear visibility even in direct sunlight, which is critical during field inspections. The OcuSync 2.0 HD transmission system provides a stable and reliable video feed up to 8 km, enhancing the ability to monitor inspections in real time. Additionally, the drone's five-direction obstacle sensing, enabled by infrared and stereo vision sensors, enhances safety during operations in confined or complex environments.

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3. Case studies

In order to assess the suitability of state-of-the-art technologies for remote bridge inspection, a pilot project involving three case studies was conducted. The case studies involved different types of bridges according to their function, structural type and structural material. Also, each case study incorporated different remote inspection techniques varying by the detail level of the inspection and the condition of the bridge structure. One thing in common for all the case studies was the implementation of the interferometric radar instrumentation in order to demonstrate the advantages of using this technique for different types of bridge inspection and their location in seismic prone area.

3.1. Simply supported steel girder railway underpass

Firstly, the investigation considered an older bridge structure located in urban area with little or no maintenance over the course of existence. The first case study structure is a simply supported steel girder railway underpass with 4 spans constructed roughly 50 years ago. The length of the longest middle spans is 14m. This bridge is frequently used as it is positioned on the main railway line in N. Macedonia (Fig. 2 – left) that reaches the main station in the capital Skopje. It is in constant exploitation with passenger and freight trains and undergoes cyclic loading and deformation a few times a day. Due to the lack of maintenance strategy and non-existence of bridge inspection procedures, the exposed steel superstructure of the bridge is heavily corroded (Fig. 2 - right). Additionally, there is spalling of concrete visible at the column faces resulting in removal of the concrete cover and reinforcement being exposed to external influences. The bearings and the rivetted connections are also heavily corroded.

Figure 2. View above (left) and below (right) the simply supported steel girder underpass.

The investigation of this bridge structure was performed using visual routine inspection and the interferometric radar IBIS-FS. Since the bridge is in full operation throughout the year, the passing of a freight train was chosen as the suitable loading for obtaining the information required.

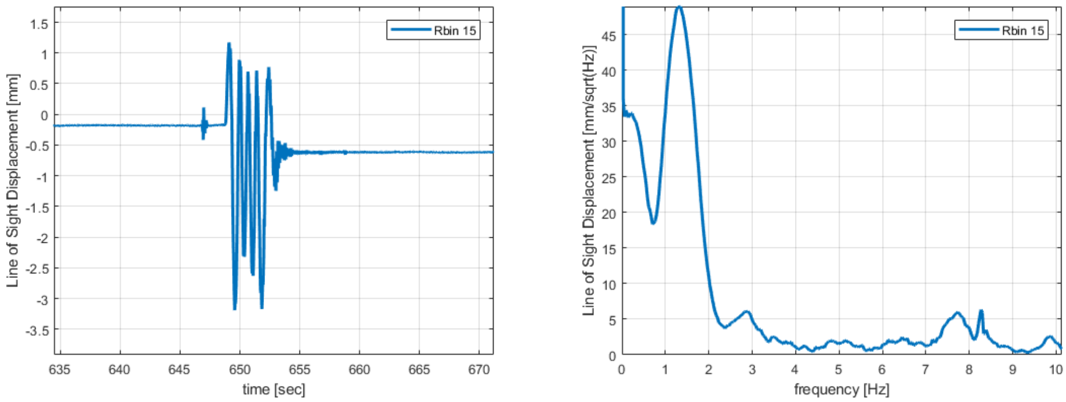

Figure 3. Time history of the bridge deformation (left) and frequency analysis of its superstructure (right).

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Without disruption of the traffic above and below the bridge structure, several key structural parameters were obtained. A line of sight (LOS) absolute displacement of 4.1mm was measured (Fig. 3 – left) which results in 13.3mm total vertical displacement from the freight train dynamic loading. The measured displacement represents 1/1050 of the length of the structure which is a parameter that can be compared with the prescribed values for maximum allowed deformations under live loading in bridge structures. It is interesting to note that a small permanent deformation was observed which can be accounted to the static system of the bridge and the small movement in the bearings during the cyclic loading from the trains. After the dynamic loading of the bridge, frequency analysis was performed on the free oscillations from the deformation time-history. The first frequency of the superstructure was evaluated at 1.3Hz (Fig. 3 – right) and that parameter gives valuable information about the condition and the behaviour of the structure, especially when considering the response of the structure during seismic events that occur frequently in this area. It was therefore concluded that the remote sensing technology can easily be implemented for fast assessment of the deformability and behaviour of the bridge structures in urban areas without disrupting the rail and road traffic during regular inspections and after seismic events.

3.2. Cable-stayed pedestrian bridge

The next case study structure is a cable-stayed pedestrian bridge over the river Vardar in Skopje. The main span is 55m long and as is the case with the steel girder railway underpass, the bridge is with little or no maintenance over the course of existence. It was constructed around 25 years ago. Figure 4 – top shows the view from the side of the bridge while Figure 4 – bottom depicts the entire bridge structure taken from the top using the UAV described in Section 2.

Figure 5. Side view (top) and view from aerial perspective (bottom) of the cable-stayed pedestrian steel bridge.

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From the visual inspection of the structural elements of the bridge, heavily corroded bridge deck and girders were observed. Additionally, the lower side connections of the stays with the girders and the substructure of the bridge were also corroded (Fig. 6). Since the upper side of the bridge stays was far from the accessible range for visual inspection, UAV was employed. Using the UAV inspection, the condition of the upper side of the stay connections with the pylons was inspected. As expected, corrosion was detected at the connection and in other parts of the upper bridge structure (Fig. 6).

Figure 6. Corrosion detection following visual and UAV inspection.

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Then, the behaviour of the case study bridge was investigated using instrumentation for evaluation of its dynamic characteristics. As previously mentioned, the interferometric radar was employed in all case study structures. Additionally, seismic sensors such as accelerometers were installed on the bridge deck to assess the accuracy of the radar measurements. The bridge was dynamically excited by applying a vertical periodic load at the midspan of the bridge in the form of pedestrians jumping on the bridge midspan. The measurements of the transversal and vertical displacement time history were obtained after the removal of the periodic load to avoid the interference from the periodic loading. The tests and measurements were performed several times for repeatability. Finally, the results of the transversal and vertical frequency analyses using the accelerometers and interferometric radar are presented in Fig. 7.

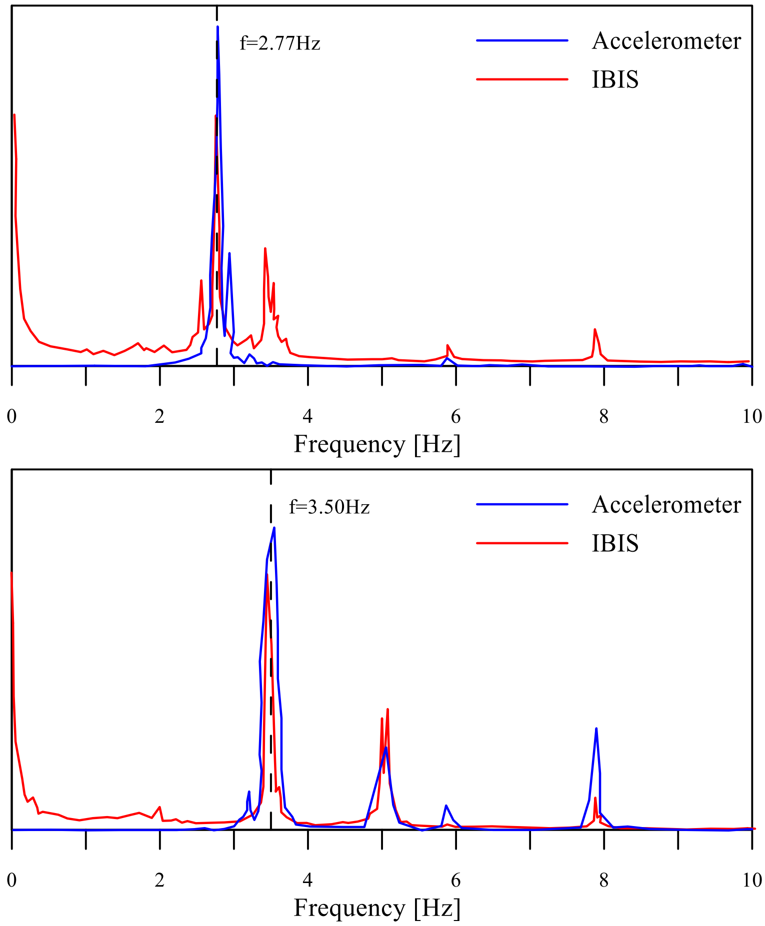

Figure 7. Frequency analysis of the pedestrian bridge deck structure for transversal (top) and vertical (bottom) direction using accelerometers and interferometric radar.

It is observed that the frequencies from the frequency analyses using the accelerometers and the interferometric radar for transversal and vertical direction are matching. Since the main characteristic of the interferometric radar is evaluation of displacements in its line of sight (LOS), the setup of the instrument with regard of the structure main axis is very important. It should be noted that for obtaining the transversal direction frequency the interferometric radar was installed on the side of the bridge. Hence, the highest amplitude peak from Fig. 7 – top displays the transversal frequency of the structure while also depicting the vertical frequencies obtained with the radar with lower amplitudes due to the three dimensionality of the displacement vector. In contrast, the accelerometer obtained only one peak in the transverse direction depicting the first transverse frequency of the structure. The same values for the vertical frequencies can be observed on Fig. 7 – bottom, which was obtained from a measurement of the bridge deck using the interferometric radar placed directly beneath the bridge structure. As a result, it was demonstrated that the interferometric radar technology for remote testing of bridge structures can accurately be employed for assessing the behaviour of cable-stayed pedestrian bridge

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without the need of additional arrangements for loading or access to the bridge deck. Combined with the thorough visual inspection using UAV, it can give detailed information on the condition of the bridge structure under consideration and can be employed without any obstacles during regular inspections and after significant seismic events.

3.3. Prestressed reinforced concrete road overpass

Finally, the last case study involves the implementation of the remote sensing technology for bridge inspection on a newly constructed bridge structure. In this situation, the interferometric radar instrument is employed to identify the modal properties of a newly built road overpass and measure the deformations under live loading. The newly constructed overpass is 21.5m long and finished with construction in 2024, Fig. 8. It consists of 6 prestressed T-section girders resting on 120cm thick end columns. Reinforced concrete slab with 15cm thickness is cast over the bridge girders.

Figure 8. View of the prestressed reinforced concrete overpass with the installed radar for measurement.

The investigation of this bridge structure involved both static and dynamic testing procedures. Namely, the static test involved placement of the live load at midspan and leaving it for 1 minute before removing it from the bridge and measuring the residual deformations (Fig. 9 – left). The dynamic test was performed using the same live load (loaded truck) and letting it move with 30km/h over the bridge (Fig. 9 – right). Displacements in the range of 1/12000-13500 of the length of the structure were observed during both measurements. However, in this case study, the weight of the live load was not measured and the efficiency of the load testing was not evaluated.

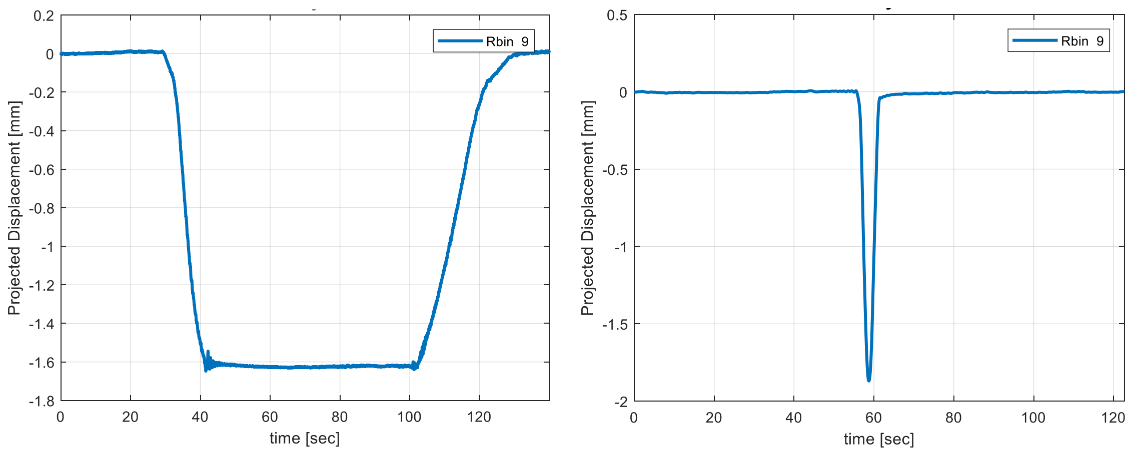

Figure 9. Deformation time-history during bridge testing: static (left) and dynamic (right).

Additionally, to produce significant excitation for modal properties estimation, an obstacle was placed at midspan and the corresponding frequency analysis was performed on the free oscillating segment of

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the dynamic time history recording. This is the common procedure for load testing of newly constructed or repaired and retrofitted bridges. The modal properties of the case study bridge were estimated using the interferometric radar and additional seismic sensor. The accelerometer was installed on the bridge deck to assess the accuracy of the radar measurements regarding this particular type of bridges. The measurements of the vertical displacement time history were obtained from the free oscillations after the live load excitation. The results of the vertical frequency analyses using a state-of-the-art accelerometer and interferometric radar are presented in Fig. 10.

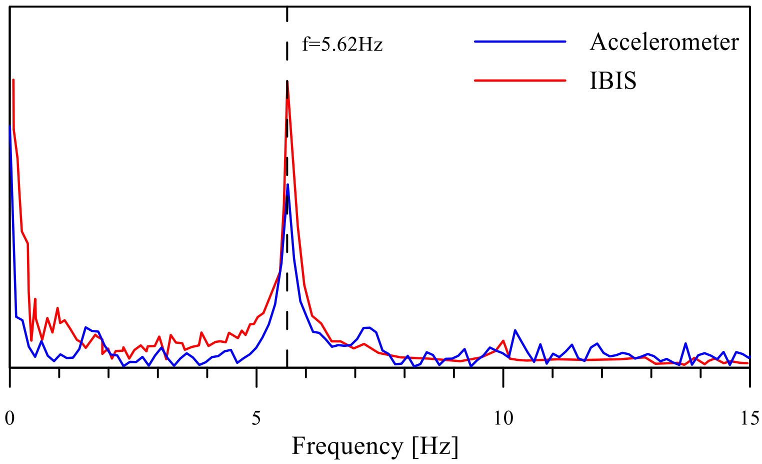

Figure 10. Frequency analysis of the prestressed road bridge deck structure for vertical direction using accelerometer (top) and interferometric radar (bottom).

It was again observed that the frequencies from the frequency analyses using the accelerometer and the interferometric radar are matching, obtaining values of 5.62Hz in both cases. Hence, it was demonstrated that the interferometric radar technology for remote testing of bridge structures can accurately be employed for assessing the behaviour of newly built prestressed reinforced concrete road bridge without the need of access to the bridge deck. The remote sensing technology using the microwave interferometric radar is evaluated to provide accurate results for both static and dynamic testing of bridges. The results from the static and dynamic load testing can be used for estimation of the real dynamic coefficient of the bridge structures and monitoring the condition of newly built bridges in a comprehensive asset management system. Additionally, the results obtained from these analyses can provide strong basis for evaluation of the structural behaviour during regular inspection and after significant seismic events in order to ensure safety of the critical infrastructure assets.

4. Conclusion

This study has provided critical insights into the current condition and performance of various bridge types, highlighting the effectiveness of integrating different testing methodologies. These methods form a robust framework for structural assessment, which is crucial for making informed decisions regarding maintenance and rehabilitation strategies. The findings emphasize the importance of regular monitoring and timely interventions to extend the lifespan and ensure the reliability of essential infrastructures during regular exploitation and after significant seismic events.

A key outcome of this research is the validation of remote sensing technology as a practical solution for the rapid assessment of deformability and behaviour of bridge structures in urban environments. The significant advantage of this approach is its ability to operate without disrupting rail and road traffic, making it particularly valuable for densely populated areas.

The study has demonstrated that interferometric radar technology can be effectively employed for the remote testing of bridge structures. Specifically, it has proven to be an accurate tool for assessing the behaviour of cable-stayed pedestrian bridges without the need for additional loading arrangements or access to the bridge deck. When combined with thorough visual inspections using unmanned aerial

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vehicles (UAVs), this approach provides a comprehensive and detailed evaluation of the condition of the bridge structure.

Furthermore, the application of interferometric radar technology has been shown to be equally effective for newly built prestressed reinforced concrete road bridges. The capability of microwave interferometric radar to deliver precise results for both static and dynamic testing underscores its value in modern bridge assessment practices. These results can be utilized to estimate the actual dynamic coefficient of bridge structures and to monitor the condition of newly constructed bridges within a comprehensive asset management system.

In conclusion, this study affirms the transformative potential of remote sensing technologies in the field of structural engineering. By enabling accurate, non-intrusive, and efficient assessments, these technologies represent a significant step forward in ensuring the safety, reliability, and longevity and a crucial tool for post-earthquake assessment of critical infrastructure assets.

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