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ASSESSMENT OF TRAM-INDUCED VIBRATIONS ON EARTHQUAKE-DAMAGED BUILDINGS

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Abstract

Operation of rail vehicle induces dynamic forces that can be transmitted to and have a harmful effect on people and structures in vicinity of rail infrastructure. When considering historical masonry structures and earthquake-damaged buildings, vibrations induced by closely positioned rail infrastructure can pose a significant challenge for structural engineers and urban planners, particularly in densely populated, heritage-rich city centres. This paper examines the impact of vibrations induced by tram traffic on the structure of earthquake-damaged buildings, through a case study of a historical masonry structure damaged in 2020 Zagreb earthquake. The main goal was to develop an analytical model for assessing the transmission of tram-induced vibrations to the foundation of an earthquake-damaged building. By utilizing transfer functions derived from measured vibration data on both the building and tram vehicle, the study aimed to evaluate the impact of track irregularities and different tram operating conditions on the vibrations affecting the building. This approach enables the assessment of potential risks associated with elevated vibration levels in the vicinity of seismically damaged buildings and provides insights for mitigating their effects on buildings structure. Results indicate that certain operational scenarios, such as track irregularities and higher tram speeds notably increase vibration amplitudes, potentially leading to progressive building damage over time. This analysis highlighted the cumulative effects of low-amplitude but repetitive vibrations on earthquake-damaged masonry, including the propagation of micro-cracks and loss of material ductility. The study emphasizes the importance of mitigating tramway-induced vibrations by incorporating these insights into structural maintenance and infrastructure planning, to protect damaged structures and enhance sustainable urban resilience in regions affected by earthquakes. Recommendations include implementation of advanced monitoring systems to promptly address and mitigate these risks, enabling targeted maintenance of tram tracks, particularly repairs of irregularities and optimization of tramway operations.

Keywords: vibrations; tram traffic; earthquake; vibro-acoustic analysis; urban resilience

1. Overview

The earthquake that struck Zagreb in 2020, with a magnitude of 5.5 (ML), highlighted decades of insufficient maintenance and inadequate construction practices, primarily within the historic city centre. The affected area spans approximately 22.2 million square meters, with residential zones accounting for 82% of this territory. Within the protected historic urban area, damage was reported to a total of 6,651 structures, of which 2,163 were classified as either unusable or temporarily unusable. Masonry buildings have been shown to exhibit significant vulnerability to seismic activity, a conclusion corroborated by historical earthquake events in Croatia. A key characteristic of Zagreb's pre-1960s building stock is its construction typology, comprising of masonry walls with timber floors and roofs, making such buildings especially susceptible to damage even under moderate seismic loads [1].

Zagreb's extensive tramway network constitutes a critical component of the city’s public transport infrastructure. The tramway infrastructure, traverses the historic city centre and is characterized by its integration into narrow streets and close proximity to adjacent buildings. Fig. 1 illustrates the tramway network layout relative to earthquake-damaged buildings within Zagreb's historic city centre. The alignment of tram routes through the urban core highlights the proximity of tram-induced vibrations to the damaged masonry structures. This paper focuses on the post-earthquake evaluation of the impact of

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tram-induced vibrations on the historic masonry buildings that sustained extensive structural damage and are located in the immediate vicinity of tram infrastructure.

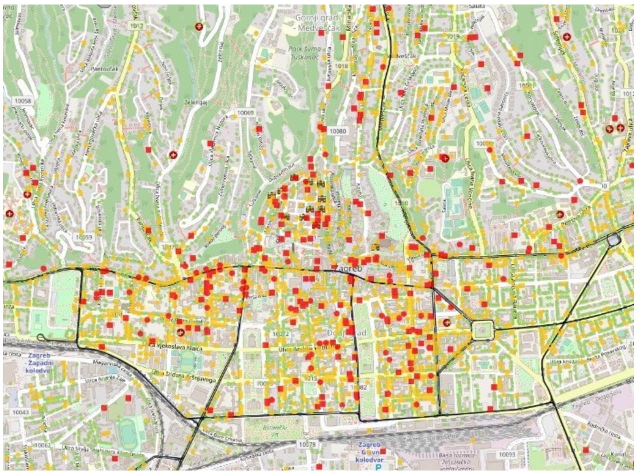

Figure 1. Tram network (black line) and buildings damaged by the earthquake categorized by initial inspections (yellow squares - temporarily unusable; red squares - permanently unusable) [2]

Buildings which are already in an unstable state are significantly more vulnerable to possible damage from vibrations or other disturbances [3]. Traffic-induced vibrations, under extreme conditions, can be detrimental to historic masonry structures. Due to their inability to resist tensile stresses, vibrations can negatively impact the structure of masonry buildings, especially under repeated loading cycles. The lack of tensile strength in masonry materials often leads to mortar deterioration and the detachment of masonry elements, ultimately reducing the overall strength of the structure. Structures with foundation settlement issues or those previously damaged in earthquakes are particularly at risk from vibrations [4]. Noticeable alterations in wall properties often emerge after exposure to tens or thousands of vibration cycles, highlighting the significance of vibration amplitude and duration as critical parameters. Traffic-induced vibrations can lead to the formation of microcracks in plaster and the gradual disintegration of walls, reducing ductility and consequently diminishing the seismic resistance of buildings [5].

The loss of vibration energy occurs during the transmission of vibrations from the source, through the surrounding soil, to the final recipient (typically the building foundations). During transmission through the soil, the attenuation is notably slower, resulting in vibration levels at the recipient being reduced by 2 to 15 dB [6]. The severity of vibration-induced damage to buildings decreases as the distance from tramway tracks increases, due to reduced transmission of vibration energy over greater distances. A minimum distance of 10 meters is recommended to effectively mitigate such vibrations [7]. Measurements of vibrations induced by rail vehicles at varying distances from the track were conducted in [8]. Once vibrations reach the building foundations, they are transmitted throughout the structure, inducing vibrations in floors, ceilings, and walls. As demonstrated in [9], horizontal particle velocities increase with height within the structure, whereas vertical velocities and accelerations remain constant. It can thus be concluded that vibration intensities are consistently greater on the upper floors of buildings. Measurements reported in [4] indicate that vertical velocity levels for foundation slabs exceed horizontal levels. Consequently, vertical vibrations are a key factor in the design strategies aimed at mitigating vibration transmission to upper floors [4].

Establishing universal and accurate thresholds for ground motions to predict structural damage is complex, as such predictions require advanced calculations. Building responses are influenced by dynamic characteristics, structural systems, material properties, and the cumulative effects of vibrations over time [10]. In evaluating the effects of vibrations on building components, peak particle velocity (PPV) has been identified as the most reliable single parameter for correlating with case history data on vibration-induced damage [3]. Unlike peak displacement and peak acceleration, PPV is relatively

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frequency-independent, making it a robust descriptor [4]. Various standards and guidelines propose different PPV limits, which are summarized in Table 1.

Table 1. Examples of acceptable vibration threshold values for buildings and occupants

PPV [mm/s]	Effect on Humans or Buildings	Reference
0.3	Perceptible for humans	[11]
1.0	Cause of complaint in residential environments	[12]
1.0	Structural damage on buildings	[13]
1.5	Structures and buildings which are especially vibration-sensitive and require protection	[14]
2.5	Strongly perceptible for humans	[11]
2.5	Limit for buildings particularly sensitive to vibrations	[15]

A peak particle velocity (PPV) of 1 mm/s is recommended as the most conservative threshold to prevent damage to buildings of cultural and historical significance, as proposed in [17]. According to HRN DIN 4150-3 [15], the maximum allowable vibration levels depend on the type of structure. For historic or sensitive buildings exposed to long-term vibrations, the standard specifies a limit of 2.5 mm/s. The European standard HRN ISO 4866:2018 [16], which addresses the measurement and assessment of vibrations' impact on structures, provides the following expected ranges for traffic-induced vibrations: frequency from 1 to 100 Hz, amplitude from 1 to 200 µm, vibration velocity between 0.2 and 50 mm/s, and acceleration ranging from 0.02 to 1.0 m/s².

2. Objectives and Methodology

The primary objective of this research was to develop a functional analytical model for the transmission of vibrations, measured at the bogie of the tram, to the foundation of the subject building. This model is based on transfer functions and utilizes recorded vibration data from both the building and tram vehicles. The study aimed to investigate the effects of specific track irregularities and varying tram operating conditions on the vibrations acting upon the building. Furthermore, by establishing transfer functions that adapt source excitation to the excitation at the building foundation, it becomes possible to assess the influence of elevated vibration levels on the earthquake-damaged buildings. The research ultimately seeks to quantify the dynamic response of the building under different tram-induced vibration scenarios, thereby providing a framework for evaluating the potential risks associated with tram traffic near earthquake-damaged buildings.

When analysing the causes of elevated vibration levels induced by tram traffic, several factors have been identified as key contributors:

- **Damaged rails** can lead to structural issues, with factors such as rail head cracks, substandard welds, and surface corrugation requiring proper maintenance to prevent further deterioration;
- **Irregularities in switch geometry** caused by poor design or inadequate maintenance can disrupt the wheel's rolling path and introduce irregularities at crossings;
- **Misaligned or deteriorated crossing profiles** at intersections require thorough maintenance, as irregular transitions in the rail surface can contribute to vibration peaks;
- **Condition of track fastenings** plays a significant role in maintaining track stability, issues such as bearing failures or displacement of concrete slabs can compromise track integrity;
- **Increased tram speeds** exacerbate dynamic forces acting on the track and surrounding infrastructure, contributing to higher vibration and noise levels.

Additionally, the evaluation sought to identify the most effective methods for small-scale, long-term vibration monitoring across multiple buildings. The initial evaluation of a typical earthquake-damaged masonry building exposed to significant tram vibrations focused on two primary locations: bogie of the tram vehicle and the masonry building itself. By instrumenting a reference tram vehicle and the affected building with accelerometers, vibration levels were measured at both the source (wheel–rail interface)

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and various locations within the structure. The collected data was then analysed using vibro-acoustical methods to determine the transfer function, allowing for the assessment of track conditions, vibration propagation, and their potential impact on the structure of the earthquake-damaged building (Fig. 2).

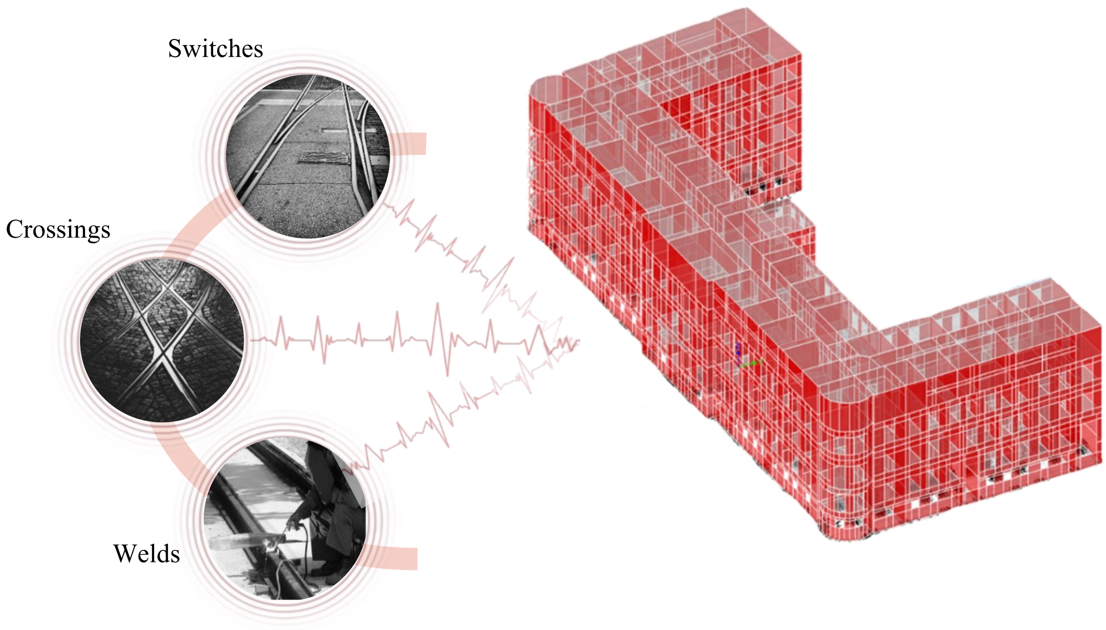

Figure 2. Conditions on rail running surface that can induce significant vibrations that can propagate to nearby masonry structures

3. Measurements and Analysis

The evaluation of tram-induced vibrations on buildings focused on assessing their transmission from tram vehicles to the track structure and, ultimately, to the masonry building, including attenuation of vibrations as they propagate through the surrounding soil. The initial phase involved measuring vibrations at the source and within the observed building during the passage of the reference tram. This was followed by a vibro-acoustical analysis to define the transfer functions. These functions were subsequently used to calculate vibration levels at various measurement points within the building, by applying the vibration levels measured at various track events on the tram network, in order to assess the impact in case they (or levels of vibrations) were to occur in the vicinity of the observed building.

3.1. Instrumentation and Measurement of Vibrations

While measuring vibrations directly at the building was essential, the tram traffic itself served as the main source of excitation. To comprehensively analyse the influence of tram vibrations, a representative tram vehicle was instrumented to measure vibration levels at the bogie level. This allowed for the assessment of track conditions and vibration amplitudes at the source (wheel–rail interface) during tram passages in front of the observed building. For the initial tests, measurements were conducted using tram TMK 2224, a 70-meter-long low-floor tram with five modular compartments, operating on three bogies in a Bo'Bo'Bo' configuration, further referred to as the reference tram. The central bogie of the tram was instrumented with accelerometers placed on the left and right sides in both the vertical and transverse directions (Z and Y respectivelly), as shown in Fig. 2. Acceleration data was collected using 10 mV/g accelerometers synchronized in time, with data recorded at a sampling rate of 4096 Hz.

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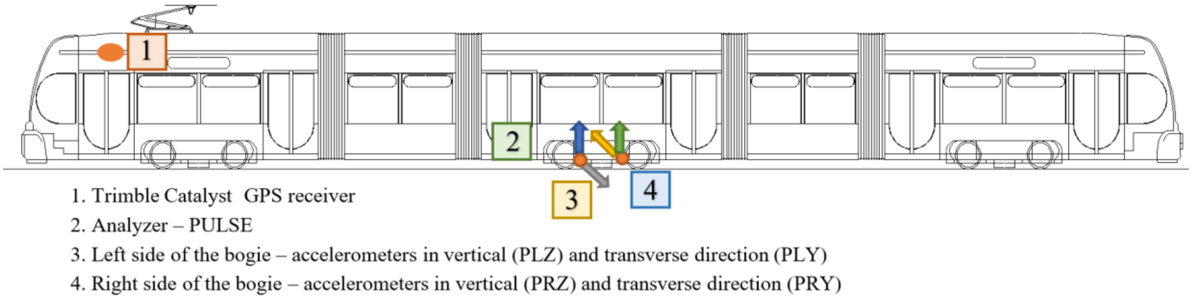

Figure 2. Position of accelerometers and GPS on reference tram TMK 2224

The testing was conducted at a masonry structure built in 1903 that exemplifies Zagreb's historic downtown architecture. The building is located in close proximity to the tram tracks, with the centerline of the nearest track only 5 meters from the building's façade. Observed building comprises of three wings (east, south, and west) and five levels, including the basement, ground floor, first, second, and third floor. Given that the south wing, which is closest to the track, was fully evacuated after the earthquake, it provided an ideal location for conducting an initial investigation into the effects of tram-induced vibrations on an earthquake-damaged structures. Following an initial inspection of the building layout and the damage caused by the earthquake, five measurement points for triaxial accelerometers were identified, as depicted in Fig. 3. The accelerometer positions were strategically selected to capture vibrations at equivalent locations across all floors. The accelerometer placements adhered to the recommendations of HRN DIN 4150-3 [15]. Data was recorded using 500 mV/g accelerometers synchronized in time, with a sampling rate of 1024 Hz.

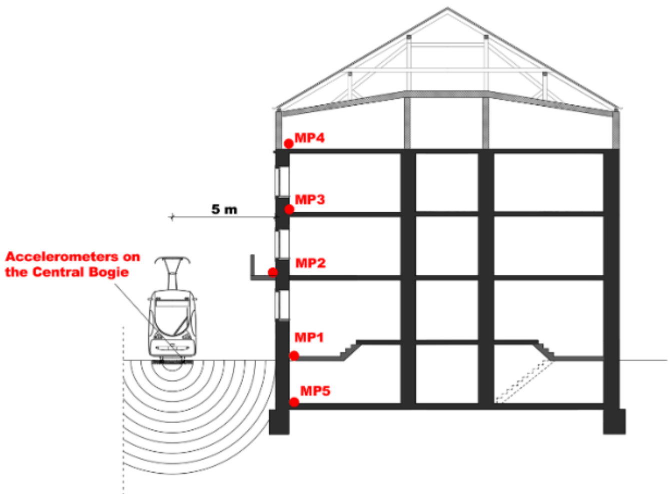

Figure 3. Positions of accelerometers and track distance from the observed building

3.2. Vibro-Acoustical Analysis

Following the measurements of vibration levels on the reference tram (Fig. 2) and measurement points within the building (Fig. 3), vibro-acoustical analysis was conducted using the DIAdem software. The primary objective was to determine the transfer function, which can subsequently be applied to calculate the impact of specific track conditions and driving scenarios on the induced vibration levels, as well as their effect on the building and the vibration levels within the structure. The transfer function is a dimensionless parameter used to calculate vibrations from various locations in the tram network under different deteriorated conditions. The data processing procedure is shown in Fig. 4.

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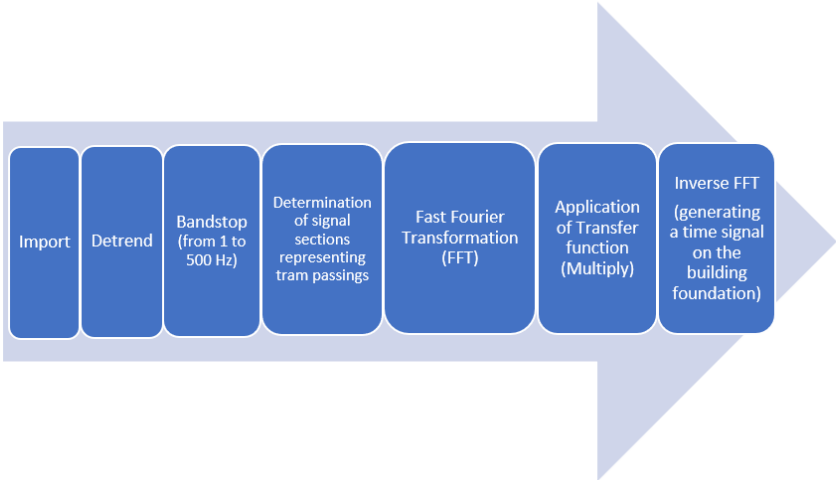

Figure 4. Diagram showing steps of data processing in DIAdem software

Tram network locations where track events generate vibration levels exceeding 150 dB were identified, which according to the study [17], are considered to potentially induce harmful vibrations (PPV>2.5 mm/s) in nearby buildings. Table 2 presents vibration levels recorded on 5 track cases of the tram network, which could cause considerable levels of PPV in the observed building at MP4, if they were to occur on the section of tram tracks in question. Most of the 5 chosen track events could cause PPV values which exceed the conservative threshold value of 1 mm/s [13], while PPV value caused by the track event on location L3 exceeds the maximum allowable level of 2.5 mm/s defined for culturally and historically important buildings [15]. Calculated levels of peak particle velocities were determined using transfer functions defined in DIAdem software.

Increased levels of vibrations at selected track events occur due to:

- L1 and L2 → degradation of the rail profile at crossings and the discontinuity of the rail profile,
- L3, L4 and L5 → degradation of the rail profile at crossings.

Measurements conducted for these track events exhibit pronounced Z-direction vibrations, primarily attributed to rail profile degradation at crossings, especially degradation of the rail head. This suggests that such vibrations are predominantly caused by rail surface discontinuities and rail wear in these track events. Given that vibrations have been analysed at the foundation level (MP5), and considering [9], it can be concluded that calculated horizontal particle velocities would be even more pronounced on higher floors of the building, as shown in the Table 2.

Table 2. Comparison of PPV values measured on the reference tram with values on MP5 and MP4 values calculated with transfer functions

Track events	**PPV [mm/s]**					
	MP5 (Z)	**ΔZ**	**MP5 (Y)**	**ΔY**	**Calculated (MP4) - Z**	**Calculated (MP4) - Y**
REF	0.14	-	0.09	-	-	-
L1	0.83	0.69	0.50	0.41	**1.96**	**1.18**
L2	0.66	0.51	0.48	0.39	**1.56**	**1.13**
L3	1.20	1.06	0.55	0.45	**2.83**	**1.30**
L4	0.55	0.41	0.40	0.30	**1.30**	**0.94**
L5	1.01	0.87	0.39	0.30	**2.38**	**0.92**

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4. Conclusions

This research provides valuable insights into the impact of tram-induced vibrations on earthquake-damaged buildings and highlights the importance of maintaining track infrastructure to mitigate vibration transmission. Tram vibrations, despite their small amplitude compared to those caused by earthquakes, can considerably affect historically sensitive masonry structures due to the high number of cyclic loadings. The analysis focused on vibration levels at the foundation level, identifying critical elements that amplify vibration levels recorded on the reference tram, such as degradation of rail profile geometry at crossings and turnouts, discontinued rail surface, substandard welds, and higher speeds.

Through vibro-acoustic analysis, transfer functions were derived from vibration signals recorded on the reference tram and the observed building using DIAdem software. These functions provide insight into how tram-induced vibrations propagate through the surrounding soil and impact nearby buildings. By modeling the vibration responses of 5 track events, from locations on the tram network in Zagreb, the study demonstrated the potential of utilizing transfer functions for assessing vibration levels at various measurement points within the building. This is particularly important if similar track events were to occur in front of the observed structure, or if significant vibration levels were to occur in the vicinity of a similar masonry building.

The research also revealed that tram vibration impacts are specially pronounced in areas where rail surfaces are degraded, such as at intersections or turnouts, leading to amplified vertical and horizontal vibrations. Given these findings, it is clear that continuous monitoring and regular maintenance of tramway infrastructure is crucial for minimizing excessive vibration levels and their transmission to buildings, especially those damaged by earthquakes. Future research should focus on the numerical modeling of building responses to tram vibrations and the development of strategies for further reducing vibration levels to safeguard the structure of sensitive buildings as well as railway infrastructure.

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