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Analysis of Tram Traffic-Induced Vibration Influence on Earthquake Damaged Buildings

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Abstract: The Zagreb 2020 earthquake severely damaged the historic centre of the city. Most of the damage occurred on historic masonry residential buildings, many of which are situated very close to the tram track. Although traffic-induced vibrations generally do not affect surrounding buildings, they can be harmful to buildings damaged by a previous earthquake. Vibrations could contribute to the further propagation of existing cracks. The effect of vibrations depends on many factors, one of the most important being the distance between the track and the building. The vibrations are highest at the source, and the energy loss occurs due to transfer through the soil to the recipients. The impact of tram-induced vibrations on earthquake-damaged buildings in the city of Zagreb is investigated in this paper. The analysis is conducted on a tramway network scale to identify critical locations by performing continuous monitoring on the tramway network and risk analysis based on the distance of buildings from the track, vibration amplitude at source, and building damage. Further investigation is based on the level of buildings to evaluate the influence of vibrations on actual buildings damaged in the Zagreb earthquake. Based on detailed signal analysis, the vibration characterization is performed, and the influence on damaged masonry buildings is evaluated.

Keywords: tram track; vibrations; earthquake; masonry structure; vulnerability

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1. Introduction

The Zagreb 2020 5.5 (ML) earthquake, although not as powerful as could be expected for this seismic region, revealed years of under-maintenance of structures and substandard building practices in the historic centre of the city. Earthquake engineering experts have been predicting such seismic events and warning the general public about the condition and vulnerability of masonry buildings [1]. It is estimated that 791,038 people were directly exposed to earthquake conditions of level-VII intensity. The total affected area occupies approximately 22.2 million square meters, with 82% of the affected area in residential parts of the city. According to the World Bank methodology, the damage to assets amounted to approximately 20% of the Croatian GDP for 2020 [2]. In the protected historical urban complex of the city, the damage was reported for a total of 6651 buildings, out of which 2163 were labelled as unusable or temporarily unusable. Masonry structures are extremely vulnerable to earthquake excitations, as past events in Croatia can prove. The main characteristic of Zagreb buildings constructed before the 1960s is that they are built-in masonry with timber floors and timber roofs, and hence, prone to damage after moderate seismic actions [3]. Construction typologies and damage classification of masonry buildings in the Zagreb urban complex are explained in detail in [4].

An extensive tramway network is the backbone of the Zagreb public transport system. The tramway infrastructure is a distinct feature of the Zagreb urban complex and has been growing together with the surrounding buildings ever since the first 8 km of the tram track was first laid in 1891 [5]. Figure 1 shows the layout of the tram network and the surrounding earthquake-damaged buildings in the Zagreb historic urban complex. This view of the tram network clearly shows that the tram passes through the very town core, using narrow streets, and it runs very closely to the surrounding buildings. The focus of the paper is on the post-earthquake assessment of tram traffic vibrations' impact on historic buildings that suffered severe damage and are positioned in the vicinity of tram infrastructure.

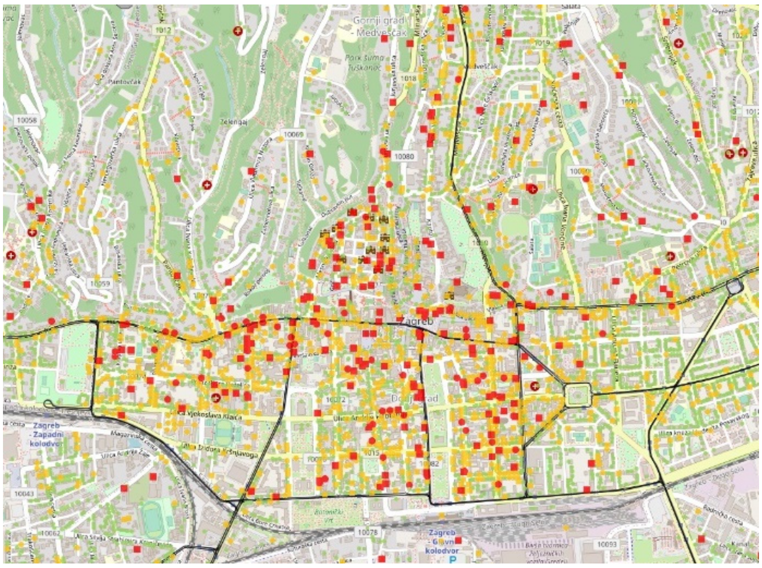


Figure 1. Tram network (black line) and earthquake damage to buildings based on initial inspection (yellow squares—temporarily unusable, red squares–permanently unusable).

If a building is in a very unstable state, then it will tend to be more vulnerable to the possibility of damage from vibration or other disturbances [6]. Traffic-induced vibrations can, in extreme cases, be harmful to historic masonry buildings. Since these buildings are not resistant to tensile stress, vibrations can have a negative effect on the building structure due to a high number of loading cycles [7]. The inability of masonry to accommodate tensile stresses causes mortar deterioration and detachment of masonry units. This can lead to strength reduction in the entire structure. Vibrations can pose a significant risk to structures having foundation settlement problems or structures damaged in previous earthquakes [7]. It is stated in [8] that traffic vibrations do not cause visible damage to the structure but can cause propagation of cracks if the structure has suffered previous damage. Traffic vibrations cause invisible changes to the wall structure. Noticeable changes in the properties of walls occur after exposure to several tens or thousands of vibrations cycles, which means that vibration amplitudes and duration constitute a significant parameter. As a result of microcracks in plaster and the disintegration of walls, the vibrations generated by traffic cause reduced ductility, which may lead to reduced seismic resistance of buildings [8]. Vibrations also disturb building occupants. In the analysis conducted in [9], it is stated that the greatest concern about the effect of vibrations is expressed with regard to sleeping and daily house activities—68% of the interviewees were disturbed by traffic vibrations at least once.

The vibration energy loss occurs during the transfer of vibrations from the source through the surrounding soil to the final recipient (building foundations). As vibrations pass through the sleeper, their value is reduced to 90% of their initial value. As they transmit through the soil, the reduction is much slower, and so, vibrations at the recipient can be reduced by 2 to 15 dB (Figure 2a) [10]. According to [11], the worst damage will occur to buildings that are less than seven meters away from the track, while the impact on buildings is negligible at distances greater than 25 meters. Vibrations caused by rail vehicles at various distances from the track were measured in [12]. The testing was conducted on the ballasted track and slab track, and the results show that the level of vibrations from the source to the recipient reduced by 10 dB. Additionally, the slabs track exhibited better results compared to the ballasted track. After the vibrations reach the foundation, they are transmitted to other parts of the structure, causing the floors, ceilings, and walls to vibrate. As shown in [4], the velocities of horizontal particles increase upwards in the building, while vertical velocities and accelerations are constant (Figure 2b). It can be concluded that vibrations are consistently higher on the upper floors of buildings. Measurements conducted in [7] show that vertical velocity levels are larger than horizontal vibration components for foundation slabs, which corresponds to the diagram given in Figure 2. Therefore, vertical vibrations are more important in the design aimed at reducing the transmission of vibrations to the upper floors [7].

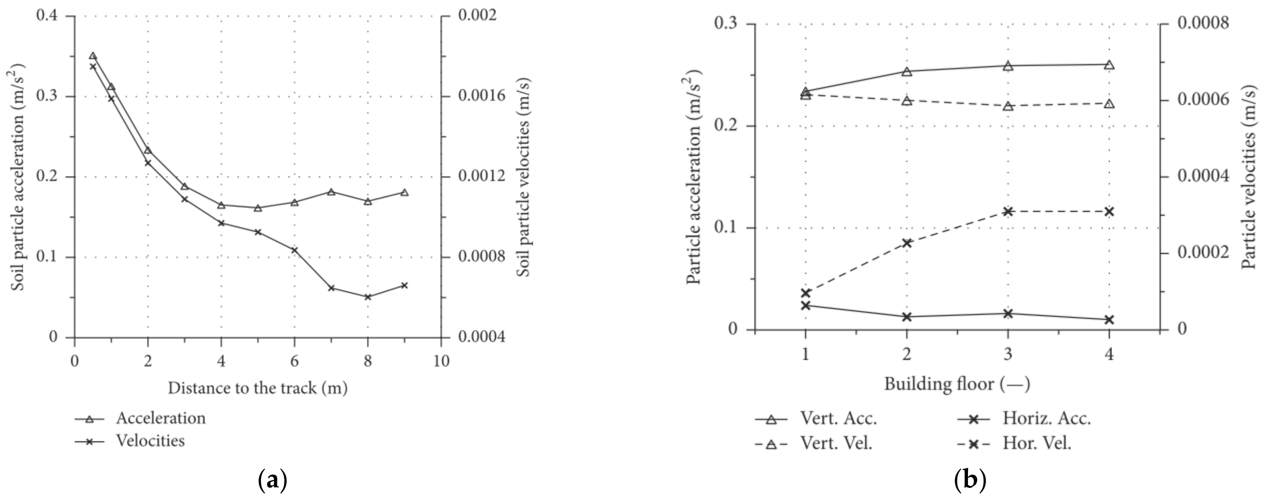


Figure 2. (**a**) Soil particle acceleration and velocities at different distances from the track; (**b**) maximum particle velocities and acceleration at different floors of the building [10].

In paper [13], the traffic vibration effect was analysed on a masonry building located near railway tracks. The building was built in 1936. Triaxial vibrations were measured at the source, and, in the building, measurements were separately made at load-bearing walls and floor structures. Based on the result of the analysis, it was concluded that the velocity of particles reduces from 1–1.5 mm/s at railway tracks and to below 0.5 mm/s at the basement of the building. Vertical components of vibrations are greater at floor structures compared to load-bearing walls. Maximum vibrations were observed at the floor structure of the first floor—2.41 mm/s. They were 1.6 times greater compared to those on load-bearing walls.

Universal and accurate thresholds for ground motions to predict building damage require very demanding calculations because building response is influenced by its dynamic characteristics and structural and material properties, and the final failure is often a result of aggregated action [14]. In assessing the effect of vibration on building components, peak particle velocity (PPV) has been found to be the best single descriptor for correlation with case history data on the occurrence of vibration-induced damage [6]. PPV is relatively frequency independent by nature, compared to peak displacement and peak acceleration [7]. Various sources offer various limits. A sampling of such limits is presented in Table 1.

Table 1. Samples of vibration threshold values for buildings and occupants.

Peak Particle Velocity (mm/s)	Effect on Human or Buildings	Reference
0.14	Threshold of perception for human	[15]
0.3	Perceptible for human	[16]
0.8	Distinctly perceptible for human	[16]
1.0	Cause of complaint in residential environments	[15]

Table 1. *Cont.*

Peak Particle Velocity (mm/s)	Effect on Human or Buildings	Reference
1.0	Structural damage on buildings	[17]
1.5	Especially vibration-sensitive structures and buildings requiring protection	[18]
2.5	Strongly perceptible for human	[16]
2.5	Limit for buildings particularly sensitive to vibrations	[19]
15	Cosmetic damage threshold for unreinforced structures	[15]

As a most conservative limit for damage on buildings of cultural and historic value, *PPV* of 1 mm/s is proposed by [17]. The Swiss standard SN640 312a [18] proposes a limit of 1.5 mm/s for especially vibration-sensitive structures and buildings requiring protection exposed to long term vibrations, defined as a vector velocity v(t) according to:

$$PPV = \sqrt{v_x^2 + v_y^2 + v_z^2}. \quad (1)$$

According to HRN DIN 4150-3 [19], maximum values of vibrations depend on the type of structure. Maximum vibrations for long-term exposure at which a historic or sensitive building will suffer no damage is 2.5 mm/s, defined as maximum vibration velocities of three perpendicular components:

$$PPV = \max\left(|v_x|, \left|v_y\right|, |v_z|\right). \quad (2)$$

Maximum vibrations suggested by DIN 4150-3 and UNI 9916 for buildings particularly sensitive to vibrations are shown in Table 2.

Table 2. Limit values for the vibration velocity in mm/s according to DIN 4150 and UNI 9916 for sensitive buildings [20].

	From 1 to 10 Hz	From 10 to 50 Hz	>50 Hz	Global
Structural damage induced by short duration vibrations	3 [a]	3 (10 Hz) to 8 (50) Hz [a]	8 (50 Hz) to 10 (100 Hz and more) [a]	8 [b]
Structural damage induced by permanent vibrations	-	-	-	2.5 [c]

[a] foundations, [b] high points, [c] entire structure.

According to the prevailing European standard relating to the measurement and estimation of the effect of vibrations on structures HRN ISO 4866:2018 [21], the following values are expected for vibrations caused by traffic: frequencies range from 1 to 100 Hz, amplitude ranges from 1 to 200 µm, vibration velocity varies from 0.2 to 50 mm/s, while acceleration varies from 0.02 to 1 m/s^2.

In contrast to probabilistic methods that use input measurements such as traffic-induced vibrations, output-only methods, such as operational modal analysis (OMA) based on long-term monitoring or periodic data collection, also present a powerful tool to detect structural damage. Changes in the response frequency content using vibration monitoring have long been recognised as an efficient diagnostic tool in safety assessment procedures for many kinds of structures. The basic idea behind this approach is the fact that natural characteristics are quite sensitive indicators of the structural integrity, i.e., they are directly related to the changes of the stiffness and damping when mass remains constant [22,23]. Such methods have successfully been used to detect structural damage on sensitive and complex masonry structures [24,25].

2. Materials and Methods

The influence of tram traffic vibrations on earthquake-damaged buildings is a long-term process because of low-level vibrations that do not cause any immediate damage. It is only the accumulated action of a considerable number of repeated vibrations that can have an influence on masonry buildings of the type that suffered the most damage in the earthquake that hit the city of Zagreb, as documented in [8]. Therefore, a comprehensive methodology had to be developed to investigate and evaluate the impact of long-term vibrations generated by tram traffic on surrounding structures. This methodology comprises:

- immediate post-earthquake evaluation of tram infrastructure and its components [26] in order to identify immediate threats to the safe operation of tram transport;
- risk analysis based on the distance of buildings from track [26], building damage score according to HCPI database [27], and vibration amplitude at source (instrumented tram vehicle) [26] used to narrow down and detect critical locations;
- initial evaluation of a typical earthquake-damaged masonry building subjected to high levels of tram vibrations—the focus of this paper;
- long-term monitoring of vibrations recorded at bogie level of an in-service tram vehicle to identify trends in vibration amplitude at source;
- long-term monitoring of vibrations on multiple damaged buildings at critical locations along the tram network to detect changes in modal parameters of buildings due to aggregated tram vibrations.

An initial evaluation of tram-induced vibrations on buildings was conducted to evaluate the nature and character of vibrations that affect the building structure, understand the vibration transfer from vehicle to track structure and further to the masonry building structure, and identify best methods and practices for the small-scale long-term monitoring of multiple buildings.

The testing was conducted in the Croatian Railways Infrastructure (HŽI) head-office building, situated in the historic centre of Zagreb at Mihanovićeva 12. The building was built in 1903 as a head office building for railway authority MAV, which is a predecessor of HŽI. It is a typical example of a masonry structure situated in the historic Zagreb downtown complex, with a basement, ground floor, first floor, and second floor. The first reconstruction followed in the 1930s when side wings (east and west) were widened. In 1964, a third floor was upgraded and constructed under the existing wooden roof structure. After the roof fire in 1977, the wooden roof was replaced with the steel frame roof structure. In this renovation, the third floor was constructed as a reinforced concrete structure. The last renovation included an upgrade of the building façade in the 1990s. In its current form, the building consists of three wings (east, south, and west), five floors, each with a gross area of 2200 m^2, Figure 3.

(**a**) (**b**)

Figure 3. (**a**) Tram type 2200 passing on the northern track in front of the HŽI head-office building (south wing), (**b**) with building orientation (red) and tram centreline (black) © OpenStreetMap contributors.

As a result of the M5.5 earthquake that hit Zagreb, the building suffered considerable damage at the level of the central staircase, partition walls, and load-bearing walls on higher floors of the building, Figure 4. The south wing was marked as temporarily unusable (PN2) according to the rapid post-earthquake assessment described in [27], while the east and west wings were marked as usable (U2) with minor damage. The building is also situated in the immediate vicinity of the tram track passing through Mihanovićeva street. The centreline of the closer track is situated only 5 m away from the facade of the building. Since the south wing, closest to the track, was completely evacuated after the earthquake, with the permission of HŽI, it served as an optimum location for performing an initial investigation of the influence of tram vibrations on the earthquake-damaged building.

Figure 4. Damage to the central staircase in the HŽI head-office building.

In the scope of the initial evaluation of a typical earthquake-damaged masonry building subjected to high levels of tram vibrations, two macro locations were examined: (1) tram vehicle at the bogie level and (2) the analysed typical masonry building. An obvious decision was to measure vibrations at the building itself, but since the main source of excitation is tram traffic, a typical tram vehicle was also instrumented to record pass-by levels of vibrations at bogie level in order to have an insight into track condition and vibration amplitudes at source (wheel–rail interface) while travelling in front of the studied building.

2.1. Instrumentation and Measurement of Vibrations on Bogie of Reference Tram

Measurements on tram bogie were conducted to acquire the best insight into vibration characteristics at the source (wheel–rail interface) and to prepare the ground for the long-term monitoring of vibrations on an instrumented in-service vehicle. For the initial testing, measurement was conducted using tram TMK 2224 (low-floor tram constructed by Končar KEV that is the main tram type with a fleet of 140 running within the Zagreb tram network), further referred to as the reference tram, Figure 5. The tram is 70 m long and features 5 modular compartments. It runs on 3 bogies (Bo'Bo'Bo' arrangement), out of which the central bogie was instrumented with accelerometers on the left and right sides of the bogie in both vertical and transverse direction as described below:

- left side of the central bogie, accelerometer in the vertical direction, marked PLZ;
- left side of the central bogie, accelerometer in the transverse direction, marked PLY;
- right side of the central bogie, accelerometer in the vertical direction, marked PRZ;
- right side of the central bogie, accelerometer in the transverse direction, marked PRY.

Acceleration data were acquired using 10 mV/g accelerometers synchronized in time, and the data were recorded at a sampling rate of 4096 Hz.

The instrumented tram TMK 2224 passed by the HŽI building on four occasions, and vibrations were simultaneously recorded on the building side and the tram side (1st pass—direction east, south track; 2nd pass—direction west, north track; 3rd pass—direction east, south track; 4th pass—direction west, north track.

(**a**) (**b**)

Figure 5. (**a**) Tram TMK2224 in the position for accelerometer mounting; (**b**) vertical and transverse accelerometers at the central bogie.

2.2. Instrumentation and Measurement of Vibrations on Typical Masonry Building

The HŽI head office building is composed of three wings (east, south, and west) and five stories (basement, ground floor, first floor, second floor, and third floor). After the initial inspection of the building, its layout, and damage suffered in the earthquake, ten measurement positions for placing triaxial accelerometers were defined, as shown in Figure 6. Measurement locations were mostly distributed throughout the south wing of the structure because it is the closest to the tram line:

- basement (position M5);
- ground floor (positions M1, M6, M7, and M8);
- first floor (position M2);
- second floor (position M3);
- third floor (positions M4, M9, and M10).

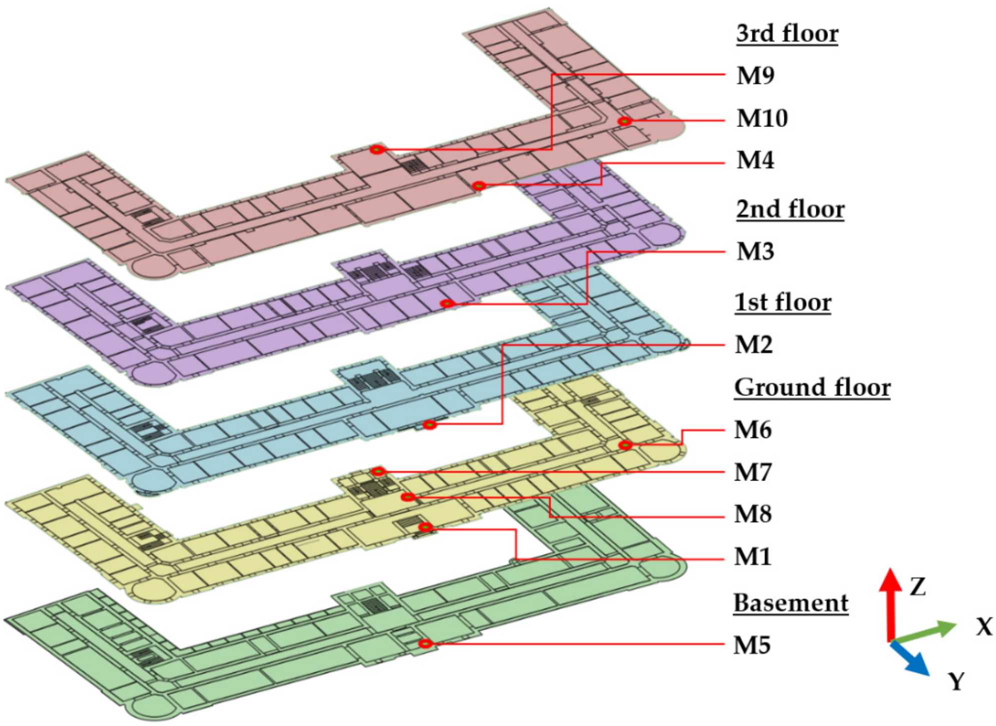


Figure 6. Layout of triaxial accelerometer measurement positions.

Accelerometer positions were carefully selected so as to capture vibrations at the same positions across all floors (M1, M2, M3, M4, and M5) to examine the propagation of vibrations to the central staircase and to the backside of the building (M6, M7, and M9) and to examine the propagation of vibrations in the southeast corner of the building (M8 and M10), where load-bearing walls from both wings meet. Accelerometer positions were also defined according to HRN DIN 4150-3 [19] recommendations so that measurement results can be calculated accordingly. Each location consists of accelerometer measuring positions in three perpendicular directions:

- X—horizontal direction, parallel with the tram track centreline and south façade;
- Y—horizontal direction, perpendicular to tram track centreline and south façade;
- Z—vertical direction, perpendicular to horizontal plane.

Accelerometers were attached to steel cubes (measuring 40 × 40 × 40 mm) in three perpendicular directions by means of magnets. The cubes were then attached with industrial glue to the solid floor or wall structure, Figure 7. Acceleration data were acquired and processed using 500 mV/g accelerometers synchronized in time, and the data were recorded at a sampling rate of 1024 Hz.

(**a**) (**b**)

Figure 7. Accelerometer placement on the (**a**) rigid floor surface and (**b**) masonry wall structure.

Accelerations in the building were recorded continuously for 24 h, together with details of all tram pass-bys in front of the building. Tram type (Figure 8), pass-by direction, and time of pass-bys were recorded for each tram. In a twenty-four-hour period, a total of 1517 tram pass-bys were recorded (numbers on southern and northern tracks were similar), which led to the traffic load of one tram per minute. This extreme traffic load is a result of various other tram routes being temporarily closed until proven safe for operation after the earthquake. The distribution of vehicle types while measuring tram vibration is as follows:

- Tram type TMK201—3%;
- Tram type TMK301—22%;
- Tram type TMK401—7%;
- Tram type TMK2100—1%;
- Tram type TMK2200—67%.

(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 8. Tram types considered in evaluation: (**a**) TMK201, (**b**) TMK 301-KT4, (**c**) TMK 401-T4, (**d**) TMK2100, and (**e**) TMK2200 [28].

3. Results

All acquired acceleration signals were post-processed in the frequency range of interest, i.e., from 0.5 to 100 Hz, in which the tram-related excitation is expected according to [21]. The vibration amplitude was calculated in 1/16 of a second intervals to obtain the peak vibration level and vibration trends. Vibrations were expressed as both accelerations in m/s^2 and as velocities in mm/s (integrated from acquired acceleration signal).

For in-vehicle measurements, vibration trends were plotted, and maximum values for each pass-by were calculated. Three-dimensional spectrograms were plotted to investigate frequency content at each tram pass-by position along the south wing of the building.

For in-building measurements, vibration trends were plotted, and maximum values were calculated for all directions (X,Y,Z) for each of the recorded vehicle pass-bys at 10 measurement locations. Three-dimensional spectrograms were also used to examine the vibrations frequency content and to identify harmful low-frequency vibrations that can interact with the building structure. Peak particle velocity was calculated according to [18,19]. $|v|_{i, max}$ was calculated at each measurement position (where i = x, y or z) based on unweighted velocity signals v_i(t).

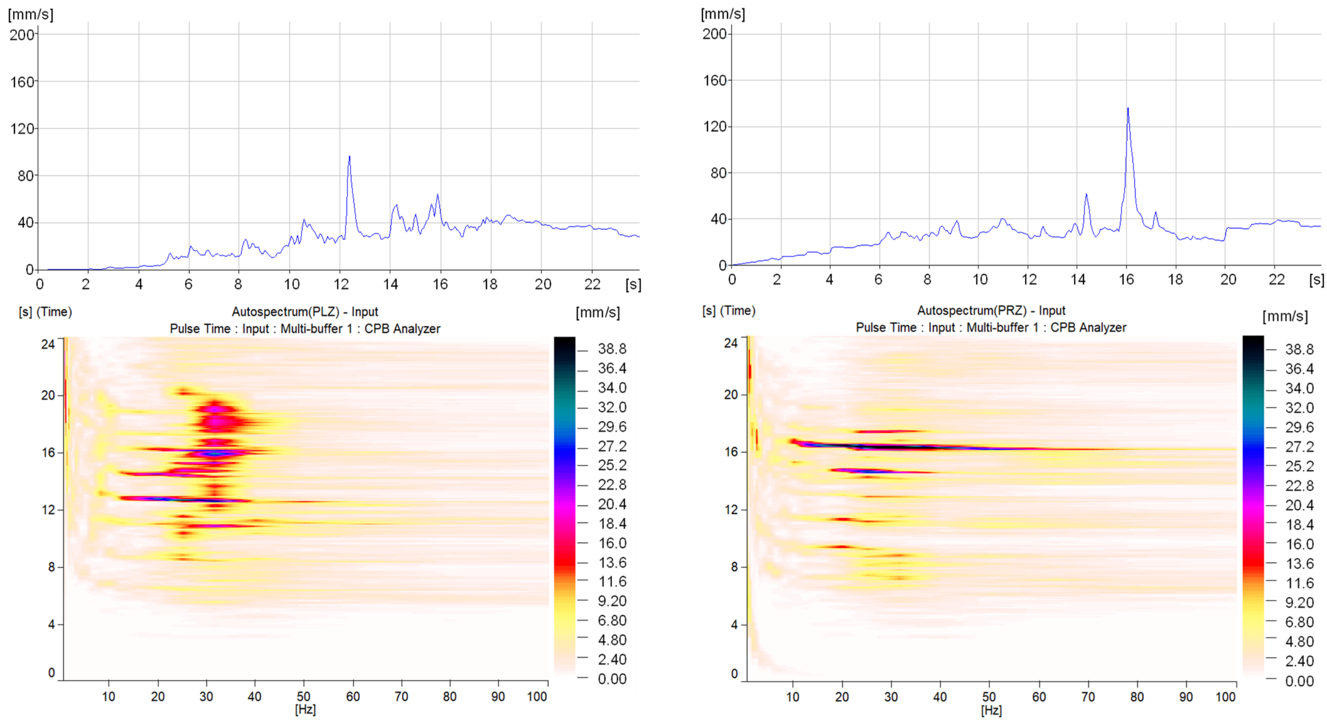
3.1. Analysis of Reference Tram Vibrations

Table 3 shows maximum vibration amplitudes recorded at the source (instrumented tram vehicle) for all pass-bys in front of the observed buildings on the left and right sides of the bogie (left and right rail). The recorded pass-by consisted of acceleration from the standstill position, continuous speed run in front of the observed building, and stop after the building was passed. The continuous speed of 30 km/h was recorded in front of the building but, due to driving conditions (intersections and traffic lights on both sides of the building), attempts 2 and 4 (north track) also included a short stop at the intersection.

Table 3. Maximum amplitude of vibrations on bogie of reference tram based on trend diagrams.

Pass-By No.	Direction	Accelerations (m/s^2)				Velocities (mm/s)			
		PLZ	PLY	PRZ	PRY	PLZ	PLY	PRZ	PRY
1	east	13.2	6.5	11.7	7.2	71	33	69	36
2	west	16/8	11.6	25.9	12.2	97	207	136	145
3	east	10.7	5.9	7.1	3.8	57	32	42	25
4	west	11.6	7.4	22.6	10.3	71	41	120	57

For all pass-bys, dominant recorded vibrations were in the vertical axis (PLZ and PRZ). The higher vibration levels were recorded on pass-bys 2 and 4 (closer to the building). The highest vibration levels were recorded on the second pass-by when the vehicle performed intensive braking at a traffic light west of the building (intersection with Miramarska street). At that moment, prominent vibrations of the bogie were observed in the transverse direction at the frequency of around 1 Hz. Three-dimensional spectrograms show that dominant frequencies vary from 25 Hz to 40 Hz, Figure 9.



(**a**) (**b**)

Figure 9. Vibration trend (top) and 3D spectrogram (bottom) of vertical vibration velocities in the second pass-by: (**a**) left side—PLZ; (**b**) right side—PRZ.

3.2. Analysis of Vibrations in Masonry Building Caused by Reference Tram

Four pass-bys described in Section 3.1 were also recorded at ten measuring positions in the masonry building. To compare four consecutive pass-bys of the reference tram, peak vibration levels (up to 100 Hz) were determined based on the waveform signal. Peak velocity values ($v_{i,\,max}$) for the second pass-by (with highest vibration levels) are presented for each location and direction in Figure 10.

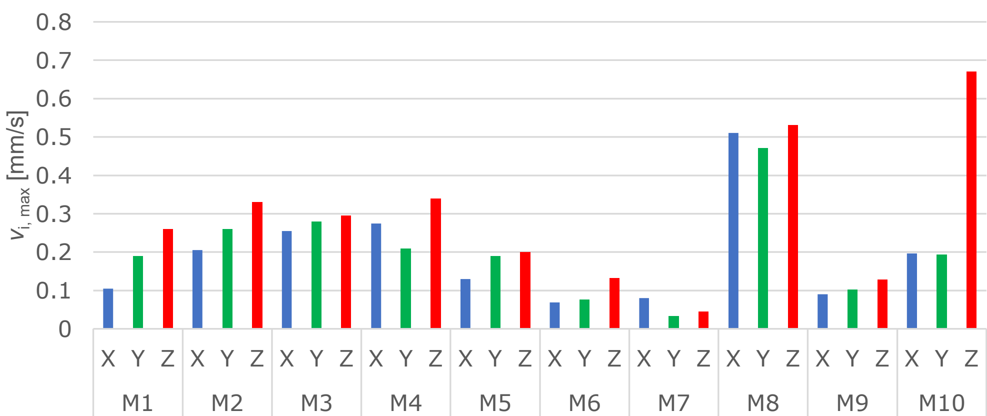


Figure 10. Peak vibration velocities measured in the building at ten measurement positions for the second pass-by of the reference tram.

The vibrations generated at the distant south track (pass-bys 1 and 3) reached 5-to-10-times lower peak values compared to vibrations generated at the north track (pass-bys 2 and 4), which was to be expected due to energy loss with the distance from the source to the receiver. Therefore, pass-bys on track closer to the building façade are further investigated. If the central position of the south façade is observed, vibrations tend to increase with the floor of the building, being the smallest at the basement level (M5) and increasing from the ground floor to the third floor (M1 to M4). On the third floor, a drop in horizontal vibration level was observed, which is probably due to the stiffer reinforced concrete structure compared to the rest of the building. It is also visible that peak velocities drop with the distance from the track (M1 → M6 → M7) on the same floor. The analysis shows that the highest vibration levels are at the south-east wing connection (M8, ground floor, and M10, third floor of the building). From vibration trends of the passing tram (Figure 9), a distinct peak in the 12th second is visible at the left side of the bogie (PLZ). This peak occurs in a broad spectrum, with the maximum at around 30 Hz. At this position, the tram changes direction (drives in an S curve), which also leads to the deteriorated track geometry when compared to other positions on the building. Additionally, the accelerometer position at the crossing of the south and east bearing walls ensures vibration transfer through the structure.

Second pass-by of the reference tram, Figure 11, induced maximum vibrations in terms of PPV when compared to any other observed pass of all trams, and it was therefore used to evaluate the level of long-term vibration exposure. Table 1 gives an overview of available thresholds for assessing the impact of vibrations on structures. According to a standard currently in place in Croatia [19], the long-term vibration exposure of sensitive structures should not exceed 2.5 mm/s of PPV calculated according to Equation (2). The maximum level was recorded in Z direction –$v_{z,\,max}$ = 0.68 mm/s, well below the allowable limit. If the Swiss standard [18] is considered, PPV calculated according to Equation (1) is 0.724 mm/s, which is also below the recommended value of 1.5 mm/s for vibration-sensitive buildings exposed to long-term vibrations. Therefore, damage occurrence due to tram vibrations has a very low probability.

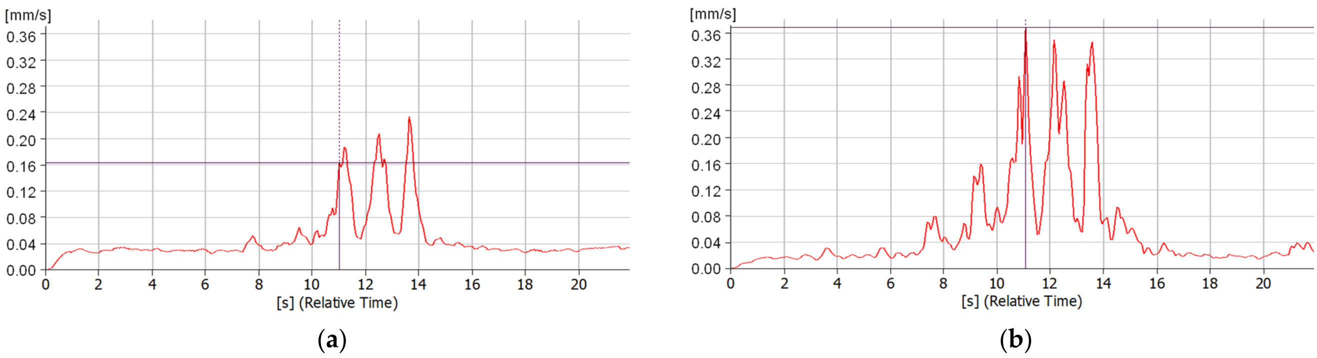


Figure 11. Vertical (Z) vibration velocity trends at (**a**) M8 and (**b**) M10 for the second pass-by of the reference tram.

3.3. Analysis of Vibrations in Masonry Building Caused by Trams in Standard Operation

Aside from the reference tram, 1507 pass-bys were recorded and analysed. Four tram types that operate on the Zagreb network were evaluated in the scope of this analysis. Peak vibration velocities in the (Z) direction are shown in Figure 12.

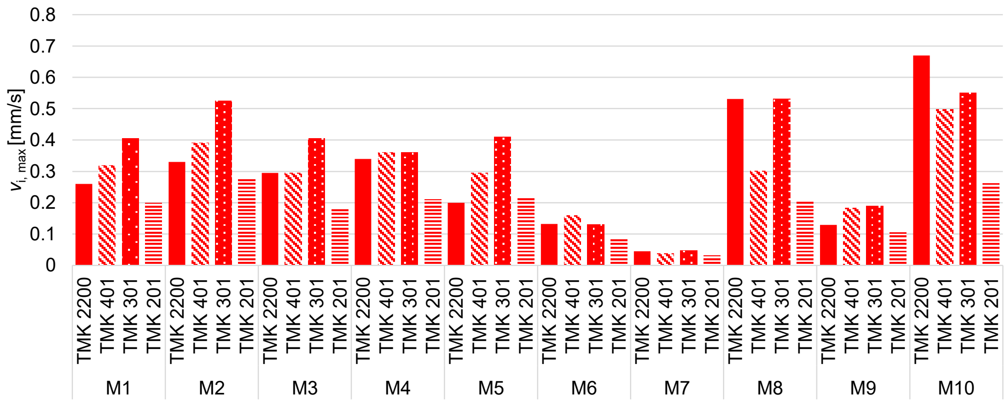
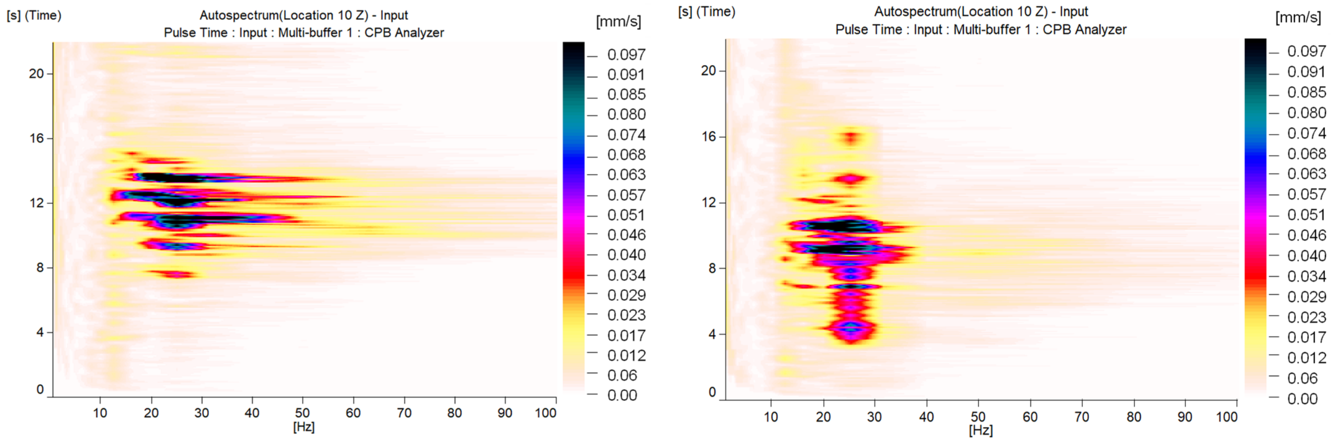


Figure 12. Peak vibration velocities in Z direction according to tram type.

By comparing four pass-bys, the highest vibration amplitudes can be observed in the vertical (Z) direction. Additionally, for all pass-bys, maximum levels were measured at location M10. For each of the tram types, vibrations at M8 are similar in amplitude for all directions. As to the south-central axis (M1–M5), the highest vibrations were induced by TMK 301 tram. Overall maximum vibration levels were induced by TMK 2200 at M10.

If 3D spectrograms for two tram types that induce the highest levels of vibrations are observed, a clear distinction can first be observed in the bogie placement and tram length, Figure 13. In addition, similar levels of vibrations occur at similar frequencies, but it can be observed that TMK 2200 induces a broader spectrum of vibrations in the building (12 Hz to 50 Hz), while TMK 301 induces a narrower spectrum of vibrations (15 Hz to 32 Hz).



(**a**) (**b**)

Figure 13. Three-dimensional spectrograms of vibration velocities at M10, vertical direction (Z), for trams (**a**) TMK 2200 and (**b**) TMK 301.

4. Discussion

If earthquake activity does not cause damage to rail infrastructure, and if normal traffic is therefore considered possible, it is important to conduct an analysis of the influence of vehicle vibrations on the surrounding earthquake-damaged structures before the actual resumption of traffic. In effect, vibrations generated by rail vehicles propagate as seismic waves, and, at that, the greatest part (67%) of such waves is transferred in the form of surface R-waves [11,12] and can cause additional damage to buildings.

During the Zagreb 2020 5.5 (ML) earthquake, rail infrastructure did not suffer considerable damage as a result of this seismic event. Significant damage was inflicted on historic buildings in the wider centre of the city and, indirectly, on tram infrastructure situated in the vicinity of damaged buildings (due to fall of parts of buildings, or due to use of heavy construction machinery during urgent repairs on buildings). Previous investigations show that vibrations caused by traffic can affect traditional masonry buildings [8,29].

This initial investigation was conducted to identify and characterize the source of vibrations and the effect it has on a historic masonry building damaged in an earthquake. The paper gives a clear overview of measured parameters, amplitudes, and frequency content of vibrations that affect the building, as caused by continuous tramway operation just 5 metres away from the building façade. It has been observed that acquisition software can clearly distinguish tram pass by and trigger automatic acquisition of such events. This is important for later long-term monitoring and storage of only crucial data for analysis (waveform, PPV, and frequency response). Additionally, a measured response revealed that energy loss that occurs with distance from the track has a great effect on measured levels of vibrations, and hence, the influence of distant track (>15 m) away from the façade can be neglected.

Several vehicle types were used in all operating conditions (steady pass by at different speeds, acceleration, deceleration). The dominant tram type in terms of the number of pass-bys (67%), as well as in the overall highest recorded PPV, is TMK 2200. The other tram type to consider is TMK 301, which induced significant vibration velocities on certain measurement positions and, on this particular section, contributes to 22% of all pass-bys. Therefore, tram type and share in the total number of pass-bys is a valuable parameter for any further location of interest.

The analysis conducted according to available probabilistic methods such as [18,19] reveals that no limit values applicable to sensitive historic buildings subjected to long-term vibrations were exceeded for the observed building. It is, therefore, safe to assume that for this building, tram traffic-induced vibrations would not cause harm and further deterioration of the bearing structure. These findings, however, give a powerful tool to perform robust and quick measurements at multiple locations along the tram network to give an indication of the tram vibration's influence on a building structure and to focus more detailed examinations, including long-term monitoring and analysis of modal parameters on structures under highest exposure to tram vibrations.

4.1. Comparison of Tram and Earthquake Response

While measuring tram vibrations, a 3.1 (ML) earthquake struck Zagreb at roughly the same epicentre [30]. It was, therefore, interesting to compare the effect of earthquake action and tram action on the same building. The seismic action of this earthquake can be represented as a response of building foundations (M5), Figure 14. The waveform and frequency analysis reveals the nature of earthquake activity, which is much lower in frequency compared to tram excitation, around 4–18 Hz, primarily in the Y direction. Building response can be monitored through different floors in the same cross-section. Frequency analysis reveals that building response is dominant in 2–3 Hz, especially at higher floors (M3 and M4), Figure 15. This distinct response was not observed with tram excitation due to the much higher frequency and lower amplitude of induced vibrations.

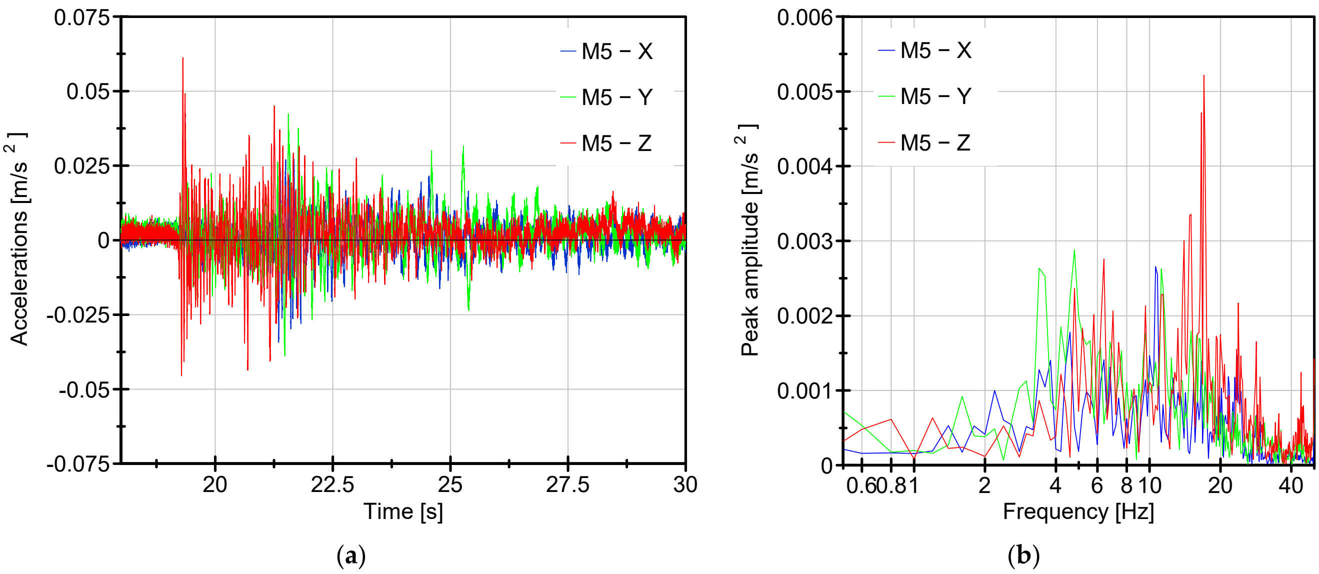


Figure 14. Accelerations represented in (**a**) time and (**b**) frequency domains, 3.1 (ML) earthquake action at the level of building foundations, M5.

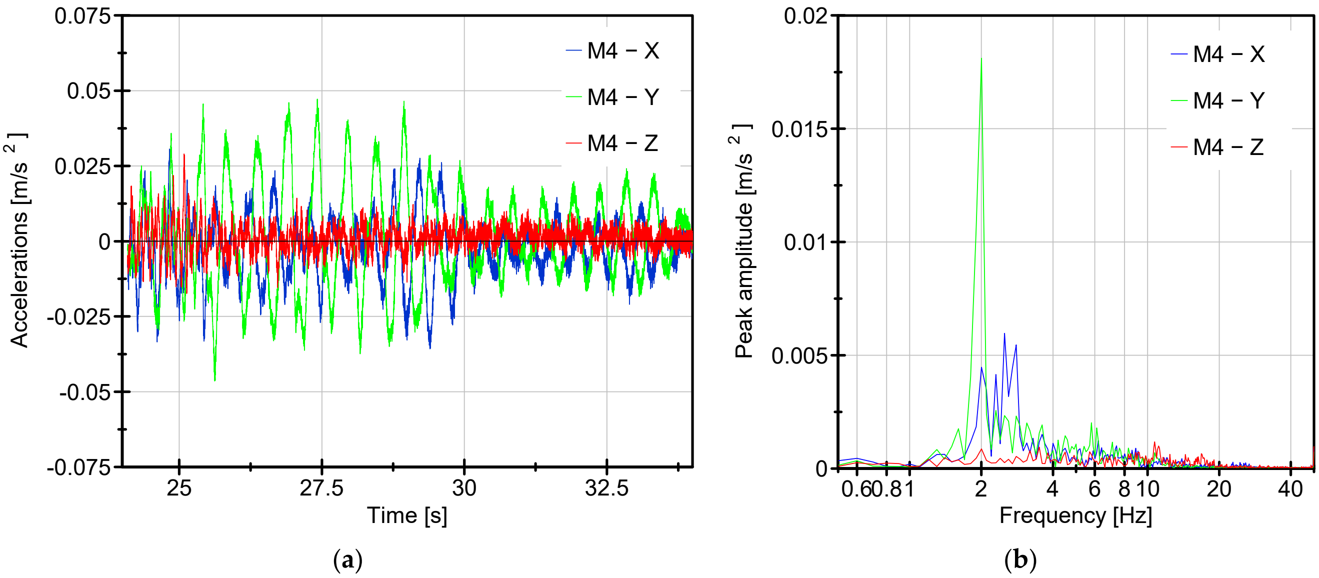


Figure 15. Accelerations represented in (**a**) time and (**b**) frequency domains, 3.1 (ML) earthquake structure response on the 3rd floor, M4.

If the 3.1 (ML) response is analysed in terms of PPV according to [19], a direct comparison to the acquired tram response can be made. The results presented for M1 to M5 clearly indicate how even small-intensity earthquake-triggered vibrations are considered harmful for historic masonry structures, Figure 16, while maximum tram vibrations trigger a much smaller response.

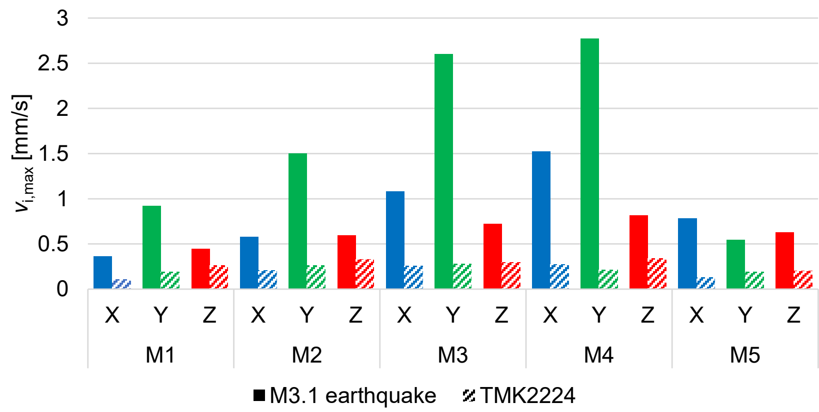


Figure 16. Comparison of peak vibration velocities generated by M3.1 earthquake and pass-by of TMK2224 vehicle.

Although this building did not suffer any immediate damage from tram operation, there are various aspects to consider for comprehending the overall influence of traffic vibrations on earthquake-damaged buildings.

4.2. Vulnerability Prior to Earthquake

Further research on this topic will concentrate on the building's vulnerability prior to the earthquake based on the presumption that it has been subjected to some level of tram-induced vibrations for over seventy years (and on some locations for more than 100 years), ever since the tram line was established along Mihanovićeva street. According to [12], this influence can lead to microcracks and the disintegration of bonding material in the masonry structure and, hence, can increase its vulnerability. Based on an extensive building damage database described in [27], the difference in the severity of damage to buildings situated in the historic urban complex is being investigated in order to determine whether traffic-induced vibrations can be a factor that contributes to vulnerability.

4.3. Long-Term Influence after Earthquake

With tram intensity and axle load increasing, it is safe to assume that vibrations will influence the building for a long time. Therefore, in cooperation with tram operator ZET, long-term monitoring of buildings damaged in the earthquake has been established. Measured parameters include the ones described in this preliminary investigation but involve a greater number of buildings at various locations along the track. It has been identified that at some locations where there are purpose-built track discontinuities (such as crossings or turnouts), peak vibration velocities in the surrounding buildings tend to be higher than the ones measured in the building analysed in this paper. Findings made after this long-term monitoring will reveal the repeating effect of vibrations on buildings. The change in resonant frequencies of monitored structural and non-structural elements could point to additional damage suffered due to exposure to vibrations. The operational modal analysis would give greater insight into the global behaviour of structures exposed to long-term traffic vibrations.

4.4. Optimization of Tram Track Components to Reduce Vibrations

In response to the high level of vibrations, several approaches can be considered in order to reduce the influence on buildings and their occupants. There is an obvious approach of renovating the building according to current standards, but the process will probably take a long time (now estimated at 10 to 15 years for the Zagreb urban complex) considering the number of damaged buildings, legal, and financial restraints, lack of workforce, etc. On the other hand, tram operator ZET investigates some other immediate, short-term, and long-term measures to reduce vibrations at the source, such as rail grinding, turnout and crossing optimization, and different track fastening system solutions that would accommodate the goal of achieving safe, smooth, and silent operation of vehicles along tram tracks, with reduced impact on surrounding buildings [31–35].

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