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Influence of tram vibrations on earthquake damaged buildings

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Abstract

Zagreb 2020 earthquake severely damaged the historic centre of the City. Most of the damage occurred on historic masonry residential buildings of which many are situated in very close vicinity to the tram track. Vibrations generated by traffic can be harmful to buildings if they have been damaged by a previous earthquake. Vibrations could attribute to propagation of existing cracks. The effect of vibration depends on many factors, and one of the most important is the distance between the track and the building. The vibrations are highest at the source and their energy loss is due to transport through the soil to the recipients, so the vibrations at the recipients can be reduced by 2 to 15 dB. In this paper, the impact of tramway induced vibrations on earthquake damaged buildings in the city of Zagreb is described. In the first step of analysis, a track segmentation was performed based on the distance between the track and damaged buildings. Each segment was assigned a score based on the risk of vibration exposure. Vibrations were measured continuously on the entire length of tram track in earthquake affected area. Further analysis of vibrations transmitted to buildings is carried out in areas with high vibration levels.

Key words: tram track, vibrations, earthquake, traffic safety, earthquake damage

1 Introduction

Vibration generated by traffic can in extreme cases be harmful to historic masonry building. Since these buildings are not resistant to tensile stress, vibrations may effect negative on structure due to high number of loading cycles [1]. Inability of masonry to accommodate tensile stresses causes mortar deterioration and masonry unit detachment. This can lead to strength reduction of the whole structure. At the structures with foundation settlement problems or structures damaged in previous earthquake traffic vibration can represent great risk [1]. It is stated in [2] that traffic vibrations do not cause visible damage to the structure, but they can caused propagation of cracks if structure has been previously damaged. Traffic vibrations causes invisible changes of the walls' structure. Noticeable changes in the walls characteristics happens after the exposure to several tens or thousands of vibrations cycles, which means that vibration amplitudes and duration represent significant parameter. As a result of microcracks in plaster and disintegration of walls, the vibrations generated by traffic cause reduced ductility, which may lead to reduced seismic resistance of buildings [2]. Vibrations are also disturbing building occupant. In analysis conducted in [3] it was concluded that the greatest concern about the effect of vibrations is expressed during sleeping and daily house activities – 68 % of the interviewees were disturbed by traffic vibrations at least ones.

Vibration energy loss occurs during transport of vibrations from source through the surrounding soil to the final recipient (building foundations). As vibrations pass through sleeper their value is reduced to 90 % of their initial value. As they transmit through the soil, reduction is much slower so vibrations at the recipient can be reduced by 2 to 15 dB (figure 1a) [4]. According to [5] the worst damage will occur to buildings whose distance from the track is less than 7 meters, and at a distance greater than 25 meters the impact on buildings is negligible. Vibrations caused by rail vehicle in various distance from the track was measured in [6]. The testing was conducted on ballasted track and slab track and results have shown that the level of vibrations from the source to the recipient reduced by 10 dB. Also, slabs track exhibited better results compared to ballasted tack. After the vibrations reach the foundation, they transmit to other parts of structure, causing the floors, ceilings, and walls to vibrate. As it is shown in [4] horizontal particle velocities increase upwards the building, while vertical velocities and acceleration are constant (figure 1b). It can be concluded that vibrations are invariably higher in the upper floors of the building. Measurements in [7] showed that for foundation slabs, the vertical velocity levels are larger than the horizontal vibration components, which corresponds to the diagram in Figure 2. Therefore, the vertical vibrations are more important in design of mitigation to reduce transmission of vibrations to the upper floors [7].

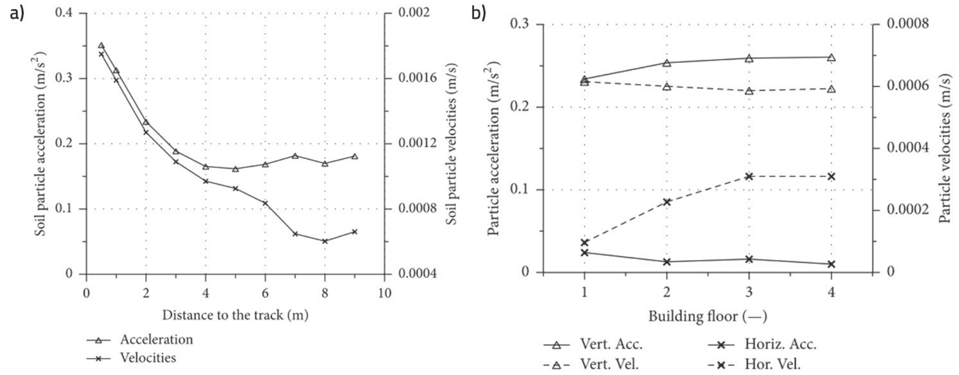


Figure 1. a) Soil particle acceleration and velocities at different distances to the track, b) ,aximum particle velocities and acceleration in different floors of the building [4]

In the paper [7] traffic vibration effect was analysed on masonry building located near railway track. The building is built in 1936. Vibrations were measured in three vertical dimensions at the source and at the building were ware separated on load bearing walls and floor structures. Based on the result analysis it was concluded that the velocity of particles reduces from 1 - 1.5 mm/s at the railway tracks, 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.

According to HRN DIN 4150-3 [8] maximum vibration at which historic or sensitive building will suffer no damage is 2.5 mm/s. In the case of continuous vibrations, maximum values of vibrations depend on the type of structure. Maximum vibrations suggested by DIN 4150 and UNI 9916 for sensitive buildings are show in table 1.

Table 1. Limit values for vibration velocity in mm/s according to DIN 4150 and UNI 9916 for sensitive buildings [9]

	From 1 to 10 Hz	From 10 to 50 Hz	> 50 Hz	Global
Structural damage induced by short duration vibration	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 vibration	-	-	-	2.5[c]
[a]foundations, [b]high points, [c]all structure				

2 Risk analysis of the impact of traffic vibrations on buildings damaged in the earthquake

After the earthquake that hit Zagreb in March 2020, great number of building in the city centre was damaged. Rapid inspection of damage and usability of building was carried out and building damages was categorised in six categories (U1 – can be used without limitations, U2 – can be used with recommendation for short-term counter measure, PN1 - temporarily unusable, detailed inspection needed, PN2- building can become usable after performing urgent interventions, N1 - unusable due to external risks, N2 - unusable due to damage) [10].

Significant part of the Zagreb old town is integrated into the public urban transport system via a tram network and tram passes through narrow streets very close to the surrounding buildings [11]. At the time earthquake hit Zagreb, tram traffic was suspended due the COVID-19 pandemic, but before resumption of traffic, preliminary risk analysis of the impact of traffic vibrations on buildings damaged in the earthquake was conduces.

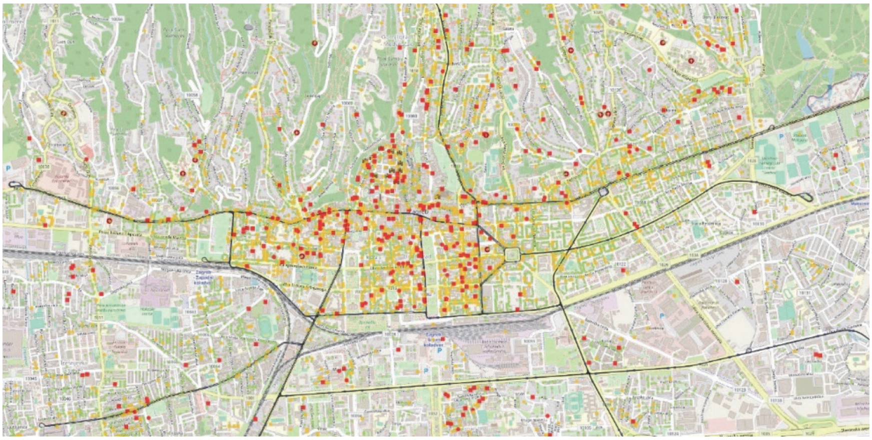


Figure 2. Tram network and earthquake damage to buildings based on initial inspection

2.1 Track segmentation based on the distance between track and buildings damaged in the earthquake

A part of analysis of influence of tramway vibrations on surrounding buildings, track segmentation was performed in GIS platform based on the distance of the track from the building and assessment of building damage. Distance between building and track was categorised in four categories:

- smaller or equal to 7 m
- between 7 and 15 m
- between 15 and 25 m
- larger than 25 m.

The analysis has shown that 35 % of tram track are located less than 7 meters away from building, 38 % of tracks are at 7-15 m, 12 % of tracks are 15-25 away and only 15 % of tracks are situated more than 25 m away from building [11]. Based on the distance between track and buildings and information on building damages, assessment of tram track vibration risk was determinate as it is shown in table 2.

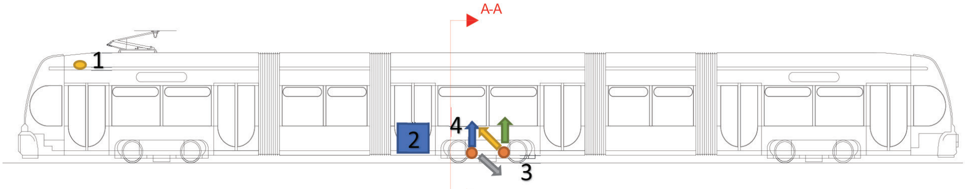
Table 2. Assessment of tram track vibration risk and its impact on earthquake-damaged buildings [11]

Risk Assessment	Level of building damage	Distance from track
1	N1, N2	< 7 m, 7-15 m, 15-25 m
2	N1, N2	> 25m
3	PN1, PN2	< 7 m, 7-15 m
4	PN1, PN2	15-25 m, > 25 m
5	U	< 7 m, 7-15 m, 15-25 m, > 25m

2.2 Analysis of vibrations at wheel-rail interface

Vibrations that spread from rail vehicle to surrounding buildings originate from the rail-wheel contact surface. Therefore, initial measurement to cover entire length of track have been made using a test vehicle of type TMK2200 with accelerometer sensors fitted to tram bogie. This test gives a detailed insight into the dynamics of the tram vehicle on the existing track infrastructure, indicates irregularities on the track that in interaction with the tram wheels induce vibrations. During the tram test drive, vehicle vibrations were measured to identify potential track sections where tram travel could cause unwanted vibrations to buildings in the vicinity.

To identify if vibration levels on the tram track have changed after earthquake, comparative analysis with vibrations measured within the *Study of Tram Traffic Development in the City of Zagreb, Report I* [12]. It was therefore necessary to preform same experiment. For this purpose, a measurement setup equal to that in the Study was used. The TMK 2224 tram vehicle with departure from the Ljubljanica depot was used to perform the measurements. The laptop and the multi-channel vibration analyser were located in the passenger compartment near the second (middle) bogie and 4 accelerometers were installed on the middle bogie of the vehicle. On the vehicle's bogie, two uniaxial accelerometers are placed near the front left wheel and two accelerometers near the rear right wheel, and the positions are selected to allow analysis of the impact of left and right rail irregularities and rail welds. In addition to the vibration data collection system, a precision GPS receiver located on the roof of the vehicle was used to geo-reference the measurement data and a high-resolution video camera in the control panel for visual inspection and signal coordination.



1. Trimble Catalysti GPS receiver
2. Vibration analyzer - Pulse
3. Right side of the bogie – Accelerometers in vertical (PLZ) and transverse direction (PLY)
4. Right side of the bogie – Accelerometers in vertical (PDZ) and transverse direction (PDY)

Figure 3. Accelerometer position on the TMK 2200 tram (section A-A)

Vibration analysis during tram vehicle traffic was conducted with the aim of assessing the risk of vibration impact on buildings damaged in the earthquake. Measurements and analysis were conducted in a way that included the following objectives:

- Determine the level of vibrations on tram track in standard traffic conditions after the earthquake (vibration measurement at normal travel speed V_{norm})
- Determine the level of vibrations on tram track in continuous uniform speed test at 20km/h as performed in 2019 study (vibration measurement at normal travel speed V_{20}).
- Determine the difference between the levels of vibration in the standard traffic conditions V_{norm} and reduced speed continuous driving speed of 20 km/h (V_{20})
- Determine the difference between vibration levels measured before and after the earthquake in order to analyse possible weak spots on the track - Comparison of measured vibration levels at a speed of 20 km/h (V_{20}) before the earthquake (Study from 2019) and after the earthquake (June 2020).

By analysing the recorded acceleration signals in the third frequency range from 0.5 Hz to 31.5 Hz, the acceleration levels were determined in time intervals of 1 second:

$$L_a = 20log_{10}\left[\frac{a}{a_0}\right]$$

where are they: L_a - acceleration level (dB); a - effective acceleration value (m/s^2); a_0 - reference acceleration 10^{-6} m/s^2; so level 120 dB represents acceleration from 1 m/s^2. Acceleration levels were continuously analysed on complete track test sections at one second intervals. Signals were processed for accelerometers PLY, PLZ, PDY and PDZ and the maximum vibration values of all measured signals are calculated. Such maximum values of vibrations (regardless of their direction and position - left or right) are indicated in figure 5 for 1 test section.

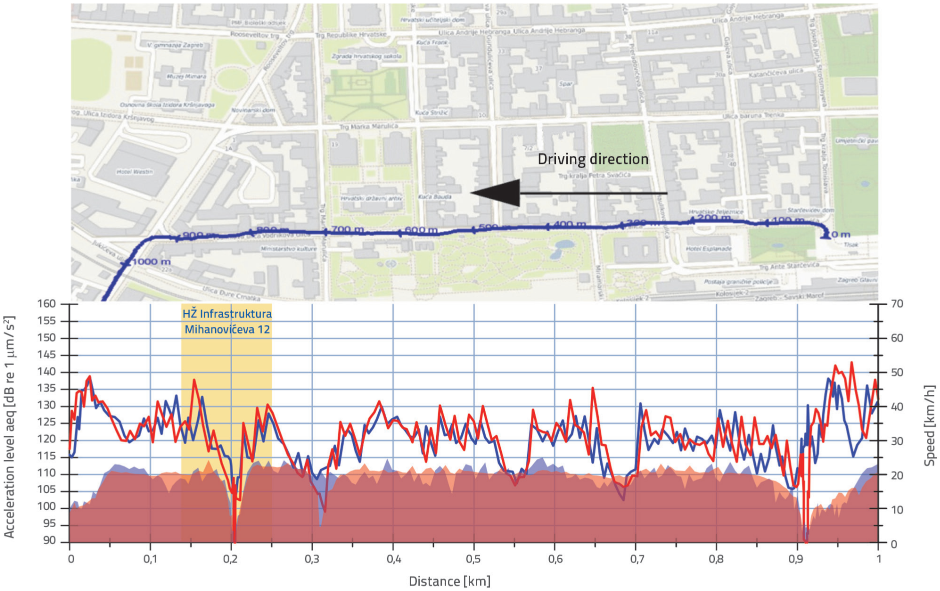


Figure 4. Vibration during tram passage along the section: Glavni kolodvor – Mihanovićeva – Vodnikova – Savska cesta (2018 = marked in blue, 2020 = marked in red), with marked passage in front of the HŽ Infrastructure building

Based on the analysis of vibrations generated by tram vehicles operating at 20 km/h, it is possible to detect points elevated vibration levels, as compared to vibrations registered in 2018, which points to possible new damage, i.e. damage possibly caused by earthquake.

2.3 Analysis of vibrations in buildings

The influence of tram traffic vibrations on earthquake-damaged buildings is a long-term process because of low-level vibrations that do no 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 mostly suffered damage in the earthquake that hit the city of Zagreb, as documented in [2]. Thus an initial testing of the influence of tram traffic vibrations on buildings was conducted for the purpose of conducting a long term monitoring of buildings that suffered damage in this earthquake. The testing was conducted on the HŽ Infrastructure head-office building built in 1903, which is situated at Mihanovićeva 12. As a result of the earthquake, the building suffered considerable damage to central staircase, partition walls, and load bearing walls on higher floors of the building. The building is also situated in the immediate vicinity of the tram track passing through Mihanovićeva street. The axis of the closer track is situated only 5 m away from the facade of this building.

Figure 5. Tram passing in front of HŽ Infrastructure head-office building

The measurement setup consisted of ten vibration measuring points (triaxial accelerometers) and five crack-width measuring points (extensometers) elaborated in [11]. The passage of all tram types, and subsequent aftershocks of varying intensity, were registered at these points.

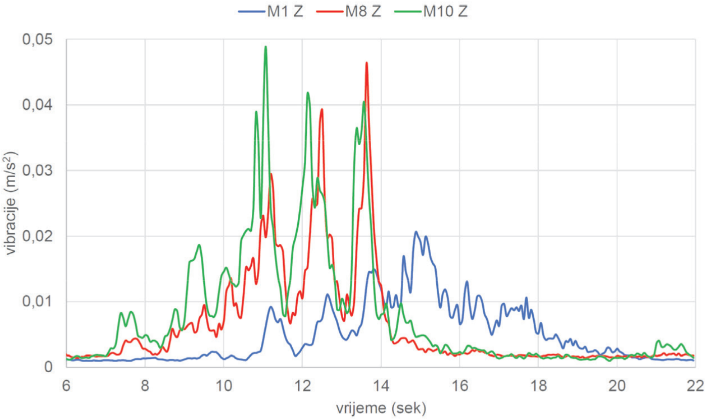


Figure 6. Vibration levels measured in vertical direction during passage of tram type TMK2200 at measuring points MMa1, MMa8, and MMa10

Some differences in vibrations generated by passage of tram vehicles were observed during preliminary investigations at some points within the building. In this respect, it is interesting to note that the highest levels of vibrations in this building were registered

at points MMa8 and MMa10, which are situated at the eastern corner of the building (Figure 5). Higher vibration levels were also registered at this locality (intersection with Ljudevita Gaja street) during vibration measurements in tram vehicle (Figure 4).
Rail induced vibrations in HŽ Infrastructure building have also been calculated according to HRN DIN 4150 [8] for all tram types and speeds that passed in front of the building in 5 days of monitoring (more than 9500 tram passes). Peak vibration velocities recorded reached 0,67 mm/s. It is important to notice that peak vibration velocity calculated according to [8] never reached values that would be marked as harmful for sensitive buildings (2,5 mm/s).

3 Further analysis and monitoring

Although preliminary analysis on one of damaged buildings in Zagreb showed that vibrations were not harmful according to [8], other locations with different levels of vibration at source (railway track) should also be considered. Critical locations for further detailed analysis are being investigated according to criteria described in Figure 6.

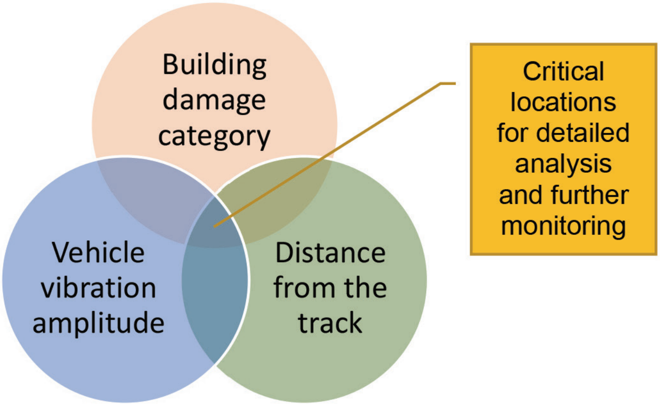


Figure 7. Detecting the most critical locations based on building damage, vehicle vibrations and distance betweeen buildings and tram track

To analyse nature of low frequency vibrations generated by tram vehicles detailed spectral analysis will be performed at locations that are in focus due to the recorded higher levels of vibration and due to the proximity of buildings. The three-dimensional representation of vibrations consists of frequency bands in one axis, a time period in another, and values of acceleration or velocity in the third axis (as shown in figure 6.).

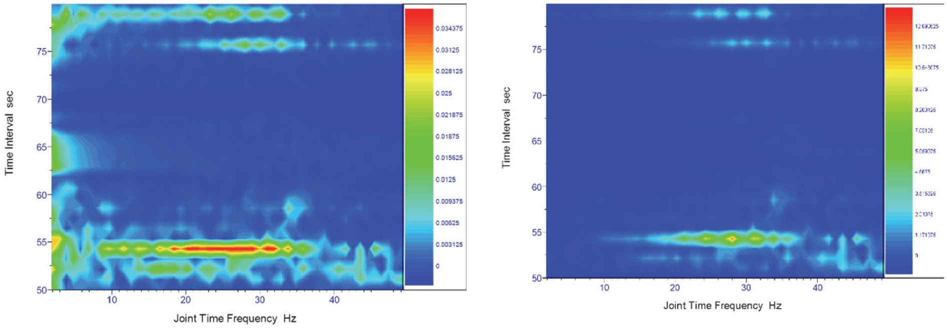


Figure 8. Joint time frequency spectrum analysis of vibration velocity on tram track near HŽ Infrastructure

On critical locations, long-term monitoring of vibrations according to [8] is planed to identify if levels can reach critical velocities that could be marked as harmful for the buildings.

In order to monitor excessive vibration events on entire ZET tram network, a new monitoring device has been installed on a tram vehicle that will allow real-time monitoring and assessment of vibration amplitudes on tram network. Results of such analysis will be valuable for identifying new critical locations that, if not properly maintained, could result in elevated vibration levels in surrounding buildings.

4 Conclusion

Rail infrastructure must be inspected after earthquake events to determine if it has incurred any damage. Measures that must be taken on rail infrastructure, depending on the distance from epicentre and earthquake magnitude, are defined in numerous guidelines. In case of strong earthquakes, damage occurs at the substructure level, which is why the entire track structure has to be repaired. On the other hand, in case of weaker earthquakes, permanent way must be checked for possible damage. If it is established during inspection that track infrastructure did not suffer any damage during the earthquake, then an analysis of the influence of rail vehicle vibrations on nearby buildings will have to be conducted before and after resumption of rail traffic. In effect, the influence of rail traffic vibrations on earthquake damaged buildings has to be analysed with special care. The Faculty of Civil Engineering of the University of Zagreb conducts, in cooperation with Končar Institut za elektrotehniku d.o.o. and Veski d.o.o., detailed analyses of such influence through long-term monitoring of typical buildings in the city of Zagreb in the vicinity of tram tracks. The analysis of results of such long-term monitoring will enable estimation of accumulated effects the frequent tram traffic has on nearby buildings.

Acknowledgment

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