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ON THE INFLUENCE OF ROAD AND RAIL TRAFFIC ON SEISMIC VULNERABILITY OF HISTORIC MASONRY BUILDINGS

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Abstract

In the event of the earthquake that struck the city of Zagreb on the 22nd of March 2020. many of the buildings in the old city centre suffered from various types of damage. Most of the masonry buildings in the old city of Zagreb are over 100 years old, and so is the tramway infrastructure running alongside the buildings. The long operational period of tramway traffic can be an important factor when we talk about the influence of traffic-induced vibrations on the seismic vulnerability of the buildings. Long-term exposure to high levels of traffic-induced vibrations can lead to mortar deterioration and detachment of masonry units. To analyse the influence of vibrations induced by tramway traffic, historic data on tram operations and earthquake damage have been investigated. Segmentation of rail tracks was made taking into consideration the distance between the track and surrounding buildings as well as the assessment of damage on the buildings after a recent 2020 earthquake. Furthermore, to inspect the influence of various types of traffic on the surrounding buildings, eight different locations in Zagreb's urban core have been chosen for statistical analysis (six streets in the north-south direction and two intersections).

Keywords: earthquake, masonry buildings, vibrations, rail traffic, road traffic, vulnerability

1. Introduction

In the city of Zagreb, a vast number of structures are built before the first seismic code was implemented (in 1964) and a high percentage of them are in the old city centre. Those buildings were built as unreinforced masonry buildings with timber or reinforced concrete floor structures with very high seismic vulnerability [1]. Because of the modern need of making the transportation system more efficient, new, special requirements are taken upon the road and rail infrastructure to take into consideration the influence that traffic could have on the surrounding buildings. Noise and vibrations coming from the traffic can be potentially dangerous for the surrounding buildings, and installations and can annoy the residents. Ground-borne vibrations and their propagation from the source to the recipient is a complex problem that could not be unambiguously defined. It is of great importance to take the problem seriously and take the vibration matter into account from the early stages of the planning process [2].

One of the main factors contributing to the historic masonry buildings' aesthetic degradation is the vibrations caused by traffic in older city centres. Even though the phenomenon is well-known and has already been debated by the scientific community, a framework to evaluate the limited vibration levels does not exist. Single events that lead to higher vibration amplitudes are synchronized bus passages as well as the irregularities of the road pavements [3]. In addition to that, an inspection of the behaviour of the building cyclic loads of road and rail traffic can be challenging because it is hard to define how many cycles could be dangerous for the historically significant buildings due to their masonry structure and lack of documentation on how and from what materials were they built [4]. Numerous factors can have an influence on the extent of traffic vibrations such as the quality of the pavement, maximum vehicle weight, duration of vibrations, average distance from the axis, and many others [5], the average distance from the axis of the road (potential damage increases with the reduction of the distance) and

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duration of vibrations being detected as one of the most important ones [2–4]. When we talk about possible negative effects on structural and non-structural elements of old, masonry buildings, traffic could be a possible cause of damage initiation and propagation. Normally, the influence that traffic-induced vibrations have on the surrounding is negligible, but in the event of some sort of individual event that could cause a natural frequency of vibration with the frequency of the excitation, additional damage can occur. In [6] long-term effect of vibrations is inspected, on the series of stone-masonry walls that have been constructed in the laboratory and possible changes in mechanical properties have been investigated. It was concluded that traffic vibrations caused the propagation of existing cracks on the previously damaged walls and that vibration amplitudes and duration represent significant parameters when we talk about the vulnerability of the structures. According to [7] structures that exhibit the problem of settlement, either at the level of their foundations or of the entire structure, and that has been subjected to earthquake vibrations are extremely vulnerable when they are subsequently subjected to traffic-induced vibrations as well.

An orthogonal grid of transportation infrastructure (road and tramway) is integrated in Zagreb historic lower town, figure 1. Both tramway and road vibrations influence the surrounding masonry buildings. Rail induced vibrations have generally higher excitation due to less damping of vibrations at the contact surface between wheel and the rail than is present in road vehicles with pneumatics. Tramway infrastructure is situated close to surrounding masonry structures. Rail irregularities such as bad or broken welds, corrugation, surface discontinuity in switches and crossings can induce high level of vibrations. Influence of tram induced vibrations in such conditions recorded on the surrounding buildings can exceed limits given by DIN 4150-3 and be considered harmful for the structure[8]. Due to these recent research findings, this paper aims to analyse whether the percentage of damaged buildings is higher in streets and intersections with tram traffic opposed to ones with road traffic only. For this purpose, a statistical analysis was carried out at several locations, which is described in the following chapter.

2. Analysis of tram-induced vibrations on a building damaged by an earthquake

2.1. Methodology

After the M5.5 magnitude earthquake that struck the city of Zagreb in 2020, more than 6500 buildings were reported damaged, of which about one-third were classified as unusable or temporarily unusable [9]. An on-site assessment of the buildings was performed, and the buildings were assigned to the following colours depending on the level of damage: green (can be used without limitations - U1, or can be used with recommendation for short-term countermeasure - U2), yellow (temporarily unusable, detailed inspection needed - PN1, or building can become usable after performing urgent interventions - PN2), and red (unusable due to external risks - N1, or unstable due to damage - N2) [10]. The most damaged buildings are historical buildings in the city centre, where tram traffic also runs in their close vicinity (less than 7 meters) [11]. These buildings have been exposed to tram-induced vibrations at some level for more than 70 years (and in some locations for more than 100 years). According to [6] and [12] tram induced vibrations cause crack widening and macroscopic crumbling of the plaster and subsequent softening and disintegration of the walls. For that reason, it is necessary to analyse and monitor the influence of vibrations caused by the operation of tram vehicles on earthquake-damaged buildings.

Buildings located less than 7 m from the street or intersection that were marked green (U1 and U2) or yellow (PN1 and PN2) during the inspection are included in this analysis. Since the buildings marked in red have suffered great structural deterioration due to their long service life, inadequate maintenance, etc., the vibrations caused by the operation of tram vehicles to which these buildings were subjected will have no effect on their degradation after the earthquake, so they were excluded from this analysis.

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2.2. Measuring locations

To determine if vibrations from the tram traffic have an impact on building damage, a statistical analysis was performed in this paper to determine the percentage of buildings marked yellow or green in the vicinity of the tram traffic streets and intersections. The analysis was performed for 6 streets with road traffic only and 3 streets with mixed tram/road traffic (Figure 1).

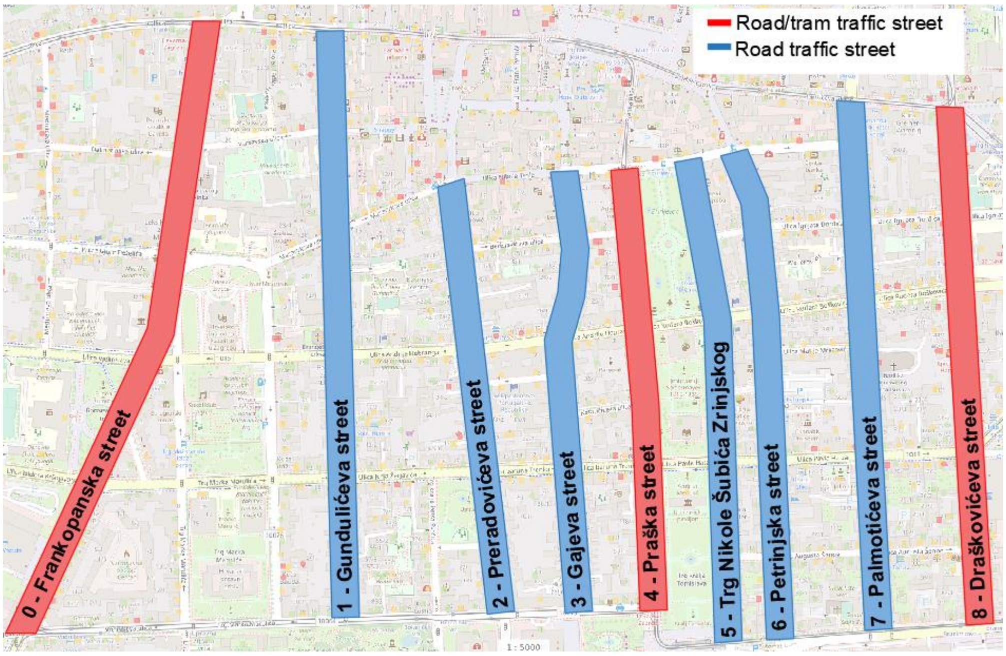

Figure 1. Display of nine streets that served as locations for statistical analysis in the north-south direction

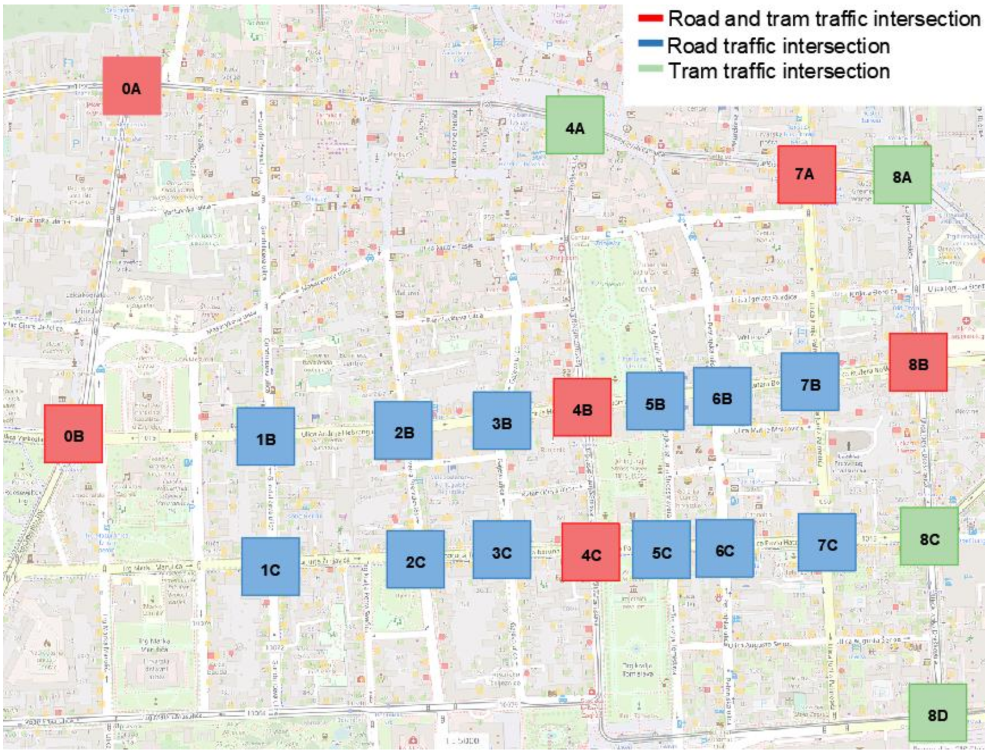

Figure 2. Display of 22 intersections in total (road-road traffic, road-tram traffic and tram-tram traffic) that were analyzed as a part of this paper

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In addition to streets, different types of intersections were studied: intersections for road traffic, intersections for tram traffic, and intersections for road and tram traffic. All analysed locations are shown in Figure 2 and described in Table 1. Different types of analyzed intersections with their location
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Table 1. Different types of analyzed intersections with their location descriptions

Road traffic intersection		**Tram traffic intersection**	
ID	**Description**	**ID**	**Description**
1B	Gundulićeva – A. Hebranga	0A	Frankopanska – Ilica
1C	Gundulićeva - Jurja Žerjavića	4A	Praška – Trg bana J. Jelačića
2B	Preradovićeva – A. Hebranga	4D	Praška – Mihanovićeva
2C	Preradovićeva -Petra Svačića	8A	Draškovićeva – Trg hrvatskih velikana
3B	Gajeva – A. Hebranga	8C	Draškovićeva – Pavla Hatza
3C	Gajeva – Baruna Trenka	8D	Draškovićeva – Branimirova
5B	Trg N.Š. Zrinjskog – Boškovićeva	**Road and tram traffic intersection**	
5C	Trg N. Šubića Zrinjskog – Pavla Hatza	**ID**	**Description**
6B	Petrinjska – Boškovićeva	0B	Frankopanska – A. Hebranga
6C	Petrinjska – Pavla Hatza	4B	Praška – Zrinjevac
7B	Palmotićeva – Boškovićeva	4C	Praška – Baruna Trenka
7C	Palmotićeva - Pavla Hatza	7A	Palmotićeva – Jurišićeva
		8B	Draškovićeva - Boškovićeva

2.3. Data analysis

Data were analysed according to the on-site assessment of the condition of the building (PN1, PN2, U1, and U2). Two different analyses were conducted, the first one for the surrounding buildings located in the vicinity of the streets (the corridor stretches 7 meters to the west and 7 meters to the east from the street axis). The second analysis was conducted for buildings 7 meters from the centre of each intersection in every direction, with different types of traffic that operates on them.

2.3.1. Streets

In streets with road traffic only the total number of buildings that are 7 m or less from the street is 320. A total of 30 buildings were red tagged in the damage assessment conducted after the earthquake, and these buildings were excluded from this analysis. Of the remaining 290 buildings, 134 (46%) were damaged during the earthquake and are marked yellow. 156 (54%) had no building damage and were labelled green. In streets that have mixed tram and road traffic, of the 87 buildings surveyed, 54 (62%) were damaged and were marked yellow. The results are shown in Table 2.

Table 2. Statistical analysis of buildings marked in yellow or red, located in road/tram traffic or tram traffic street

Type of street	**PN1 & PN2**	**U1 & U2**
Road traffic street	**46%**	**54%**
Tram/road traffic street	**62%**	**38%**

Since a larger number of damaged buildings (marked yellow) were found in the tram/road traffic street, an analysis of the tram traffic load in each tram/road traffic street was performed. The results are shown

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in Table 3. In addition to the traffic load, the percentage of damaged buildings was also analysed for each location separately concerning the total number of yellow and green buildings in the observed location. From the table, it can be seen that a higher traffic load does not necessarily result in a larger number of buildings damaged during an earthquake.

Table 3. Analysis of tram traffic load and percentage of damaged buildings in the tram/road traffic street

Tram/road traffic street		
ID	Tram traffic load [Mtpa]	Buildings marked PN1 and PN2 [%]
0	14.86	77
4	5.68	75
8	6.19	49
Mtpa- Million Tonnes per Annum		

2.3.2. Intersections

The total number of buildings near the road and tram traffic intersection is 22. Only 1 building is marked in red and is excluded from this analysis. Of the remaining 21 buildings, 16 (76%) are marked yellow, indicating that they are temporarily unusable and require a detailed inspection or urgent intervention. The total number of buildings at road traffic intersections that are 7 or fewer meters from the observed intersection is 68, of which 8 buildings were marked red in the damage assessment and are excluded from this analysis. Of the remaining 60 buildings, 32 (53%) were marked yellow and 28 (47%) were marked green. At the tram traffic intersection, 18 buildings were recorded, 3 of which were marked red in the damage assessment and are excluded from this analysis. Of the remaining 15 buildings, 3 (20%) were marked yellow and the remaining 12 (80%) were marked green. The results are presented in

Table 4.

Table 4. Statistical analysis of the yellow or red-marked buildings at the different types of intersections

Type of intersection	**PN1 & PN2**	**U1 & U2**
Road and tram traffic intersection	**76%**	**24%**
Road traffic intersection	**53%**	**47%**
Tram traffic intersection	**20%**	**80%**

As can be seen from the results, a high percentage of the buildings marked yellow are located near road/tram traffic intersections. The tram traffic load and the percentage of damaged buildings near road traffic and road/tram traffic intersections were analysed (Table 5). The percentage of damaged buildings for each location is calculated concerning the total number of yellow and green buildings at the observed location. It can be concluded that a high tram traffic load does not result in a higher number of damaged buildings near these intersections.

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Table 5. Analysis of tram traffic load and percentage of damaged buildings in the tram/road traffic street

Road and tram traffic intersection			**Tram traffic intersection**		
ID	Tram traffic load [Mtpa]	Buildings marked yellow [%]	ID	Tram traffic load [Mtpa]	Buildings marked yellow [%]
0A	25,46	67	4A	25,46	-
0B	14,83	50	8A	25,97	11
4B	5,68	0	8C	9,31	67
4C	5,68	100	8D	17,13	50
7A	19,78	100	*Mtpa- Million Tonnes per Annum*		
8B	6,19	75			

3. Conclusion

Although the vibration amplitudes generated by traffic are generally low, they can be harmful to historic masonry buildings because of the numerous cyclic loads. Since masonry buildings are not resistant to tensile, these vibrations cause damage to the plaster and detachment of masonry elements, which can gradually lead to reduced resistance of the entire structure. Structures that exhibit the problem of settlement, either at the level of their foundations or of the entire structure, and that have been subjected to earthquake vibrations are extremely vulnerable when they are subsequently subjected to traffic-induced vibrations as well.

Based on performed analysis it can be seen that there is larger number of damaged buildings in streets and intersections that include tram traffic. Based on traffic load analysis, however, it cannot be concluded that higher traffic load leads to greater building vulnerability. From this preliminary analysis therefore it cannot be claimed that the frequent exposure to vibrations caused by tram traffic caused major difference in vulnerability of buildings after the earthquake in Zagreb in March 2020. To obtain more accurate results, the analysis needs to be performed on a larger sample with more data - e.g. the exact condition of the buildings based on detailed inspection after earthquake, the year they were built and renovated, the type of buildings, traffic load, etc. Also further analysis should include wall and mortar testing such as shear tests and flat jack tests [13] in characteristic buildings under considerable traffic load.

This preliminary study and literature indicate that the vibrations caused by traffic will lead to the propagation of cracks in historic buildings damaged by earthquakes and will certainly cause inconvenience to the residents who live and work in such buildings. Therefore, especially in the historic urban areas where tram traffic runs in the immediate vicinity of buildings, as in the city of Zagreb, it is of great importance to continuously monitor vibration levels. In this way, changes and increases in the vibration level can be detected in time and appropriate measures can be taken to ensure that the vibration level remains within the permissible values specified in the standards.

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