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Analysis of seismic action of the tie rod system in historical buildings

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Abstract

Tie rods are typically used to transfer axial forces and prevent unwanted displacement on vaults, walls, arches, and buttresses in historical buildings. In order to verify their load-bearing capacity and to identify potential structural damage risks, it is very important to determine the forces transferred by tie rods and the corresponding stresses. Due to the often lack of project documentation for historical buildings, determining the axial forces and verifying the load bearing capacity can be very challenging. This paper presents the determination of axial forces in tie rods and the analysis of seismic actions on it by combining experimental and numerical analysis and finite element model updating.

Key words: operational modal analysis, Finite element model updating, tie-rods, dynamic parameters

1 Introduction

Displacements that occur in historical buildings can be resisted by tie rods that support masonry walls, buttresses, arches, and vaults. They are subjected to axial tension and are an important element in controlling horizontal forces and displacements caused by static and dynamic loads associated with seismic action. In extreme cases, the tie rod can reach the maximum load bearing capacity due to high stress or pulling out of the anchorage (Figure 1). Both cases may result in a loss of structural integrity. Therefore, the value of internal tensile force in such systems is often a topic of discussion.

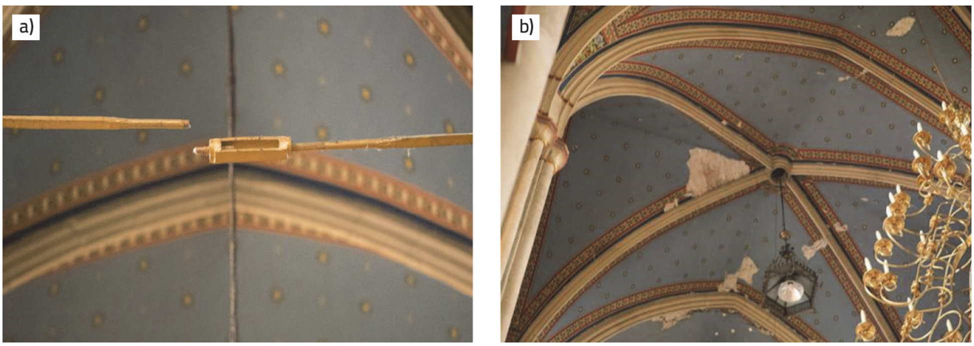


Figure 1. a) Damaged tie-rod (Reaching a maximum bearing capacity) b) Damaged vaults after a Construction disaster in a Cathedral of the Assumption of Mary, Zagreb

There are several uncertainties in determining the forces in these elements, which include complex boundary conditions [1-4], geometric and material properties [5].Several approaches are used in estimating the value of forces in tie rods and these are static[6], dynamic [7] and mixed approach [8]. In addition to the above approaches, a combination of experimental and numerical tests based on the model updating approach is often used. Model updating has emerged in the 1990s as a topic of great importance in the design, construction and maintenance of mechanical systems and structures. It refers to the update of the finite element numerical model to adopt more precise and accurate structural dynamic. In this approach, the numerical model is updated based on known dynamic parameters obtained through experimental tests. The finite element model updating is performed through the correction of material and geometric characteristics and boundary conditions. The paper presents an analysis of seismic actions on iron tie rods in the Cathedral of St. Jacobs in Šibenik (Figure 2).
Based on the experimental testing and the application of the operational modal analysis, the dynamic parameters - frequencies and mode shapes of the structure and tie rods were determined. A local initial model of the reference iron tie rod was developed. Based on the dynamic parameters and the application of the corrected analytical equation [9], the local initial model was updated and the value of the force in the reference tie rod was determined. The methodology applied to the reference tie rod was extended to other tie rods and thus the values of the forces in the tie rods were determined.

Figure 2. a) Cathedral of St. James in Šibenik b) Tie rods in cathedral of St. James in Šibenik

After updating the local numerical model of the reference tie rod, the initial global model of the cathedral was updated by varying the modulus of elasticity of the stone and the boundary conditions. An analysis of the internal forces and stresses in the tie rods of the updated global model of the cathedral was performed, taking into account the seismic action characteristic for Šibenik. In the following, Chapter 2 describes the procedure of the performed experimental determination of the dynamic properties of tie rods and the cathedral. Chapter 3 describes the performed numerical analysis of the initial and updated local and global numerical models of the tie rod and cathedral. Chapter 4 presents the results of the analysis of the internal forces and stresses in tie rods caused by seismic action.

2 Experimental analyse

Within the experimental analysis of the Cathedral of St. Jacobs in Šibenik by classical experimental (EMA) and operational modal analysis (OMA), the dynamic parameters of the structure and a certain number of tie rods were determined. The OMA of cathedral was conducted by roving three accelerometers in several points on structure and using two accelerometers as a referent. Frequency domain decomposition (FDD) were used to estimate natural frequency (Table 1.) which were read from the characteristic record (Figure 3).

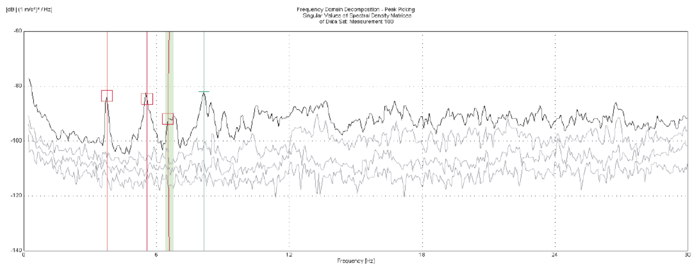


Figure 3. Characteristic record of frequency domain decomposition for cathedral

Table 1. Experimentally obtained natural frequencies of cathedral

Mode	**Natural frequency** [Hz]
1	3,75
2	5,55
3	6,56
4	8,06

In addition to the natural frequency of the whole structure, dynamic parameters for 24 tie rods were also obtained. The natural frequencies were determined for 24 tie rods, while both the natural frequencies and mode shapes were determined for six tie rods, which are the subject of this paper. For the sake of the simplicity, of the tested tie rods, one was taken as a reference for which a detailed analysis was conducted. The arrangement of measuring points on the reference tie rod is shown on the Figure 3.

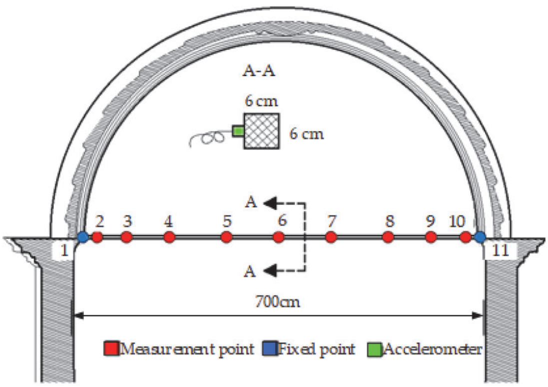


Figure 4. Reference tie rod with measuring points and dimensions

The OMA was performed by roving four accelerometers through two measurement stages, using a one as a reference. The tie rod was excited by randomly using a rubber impact hammer. Frequency domain decomposition and enhanced frequency domain decomposition were used to estimate the modal parameters (Figure 4). The values of the experimentally obtained natural frequencies for concerned mode shapes were read from the characteristics record (Figure 5).

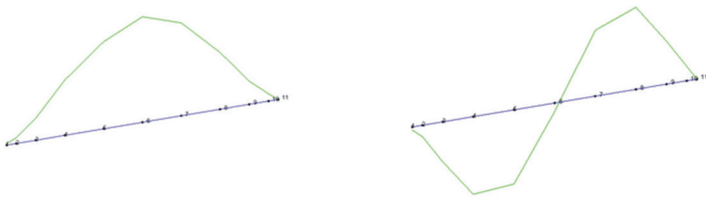


Figure 5. Experimentally obtained mode shapes for reference tie rod

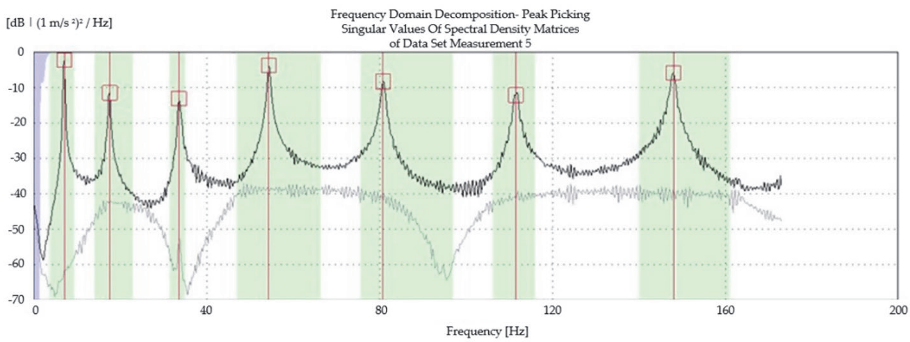


Figure 6. Characteristic record of frequency domain decomposition for reference tie rod

3 Numerical analysis

The experimentally obtained results were used to update the numerical models of tie rod and cathedral. Both local and global numerical model was developed in SAP2000 software (Computers and Structures, Walnut Creek, CA, USA). The numerical model of the tie rod was developed as the Euler-Bernoulli beam element. In a global model of cathedral columns, arches and tie rods were developed as beam element, while walls, roof, and floors were developed as a shell-tick element. A detailed description of the initial local and global model and the process of their model updating is described in the next chapter.

3.1 Tie rod numerical modal

Based on the available data, a local initial numerical model of the reference tie rod was first developed. The performed numerical modal analysis determined the dynamic properties of the tie rod, which were compared with the experimentally obtained properties. The comparison of these two data sets were carried out in the form of comparison of numerical values of natural frequencies, overlap of mode shapes and by applying RMSE factors [10]. Based on the comparison results, the numerical model was update by adding rotational springs whose stiffness value was determined by an iterative procedure. During the iterative procedure, a change in the RMSE factor values was monitored as a function of the spring stiffness values (Figure 6).

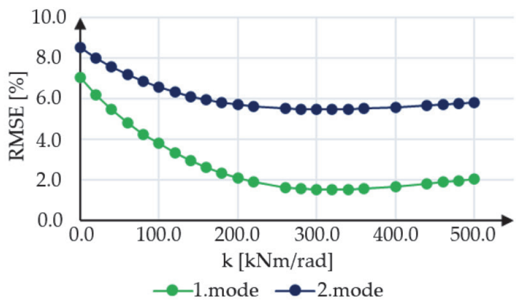


Figure 7. Changing the RMSE coefficient values as function of the spring stiffness values

The appropriate spring stiffness for observed mode shapes were selected when the RMSE factors reached the minimum values. For the selected spring stiffness, the force value in the reference tie rod was determined using a numerical model. Based on the well-known equation for determining the axial force [11, 12] the boundary condition parameter κ proposed in the literature [11, 12] is adjusted to the corresponding spring stiffness of the reference tie rod. Based on a certain dimensionless coefficient κ, known experimentally determined values of natural frequency, the values of forces and stresses in the remaining tie rods are determined (Table 2).

Table 2. Values of forces and stress level in iron tie rod for the observed mode shapes

		2B-C		**3B-C**		**4B-C**		**5B-C**	
Mode Num.	κ	**P_n** [kN]	σ_n [MPa]	**P_n** [kN]	σ_n [MPa]	**P_n** [kN]	σ_n [MPa]	**P_n** [kN]	σ_n [MPa]
1	3.534	115,8	38,3	149.6	36.5	132.1	36.7	159.4	34.5
2	6.777	144.7	47.8	158.8	38.8	167.7	46.6	207.9	45.0
Mean values		130.3	43.1	154.2	37.7	149.9	41.6	183.6	39.7
		6B-C		**7B-C**		**7-8B**		**7-8C**	
Mode Num.	κ	**P_n** [kN]	σ_n [MPa]	**P_n** [kN]	σ_n [MPa]	**P_n** [kN]	σ_n [MPa]	**P_n** [kN]	σ_n [MPa]
1	3.534	122.8	33.0	170.8	54.5	166.3	53.0	215.2	59.8
2	6.777	137.2	36.9	188.7	60.2	208.1	66.4	219.6	61.0
Mean values		130.0	34.9	179.8	57,3	187.2	59.7	217.4	60.4

3.2 Cathedral numerical model

After the force values in tie rods are determined, the global initial model of the cathedral is approached. Based on the known structural characteristics and the available data, a global initial model was developed. The natural frequency values were determined during the numerical modal analysis performed. The numerically determined values were compared with the experimentally one. Based on the comparison results, it was concluded that the numerical model needed to be updated. For the known experimentally determined natural frequency values, the initial global model of the cathedral was updated by correcting the boundary conditions and the modulus. There were three possible cases of boundary conditions. The first case was a hinge, the second was a clamp and in the third case the boundary condition was simulated as a Winkler spring [13]. The natural frequency of the first model was closest to the experimentally obtained values. This model was taken as a reference for the next step of the model updating procedure. In the second step, the value of the elastic modulus of the stone was iterated on the selected numerical model. In this way it was ensured that the numerically determined natural frequencies corresponded to those determined experimentally. During the iteration, the change in natural frequency as a function of elastic modulus was monitored (Figure 9.).

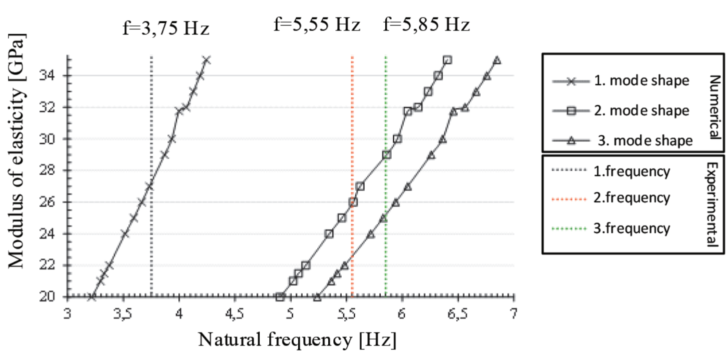
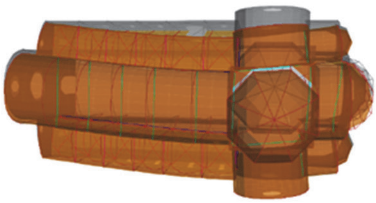
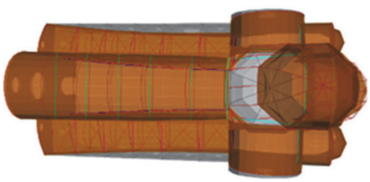
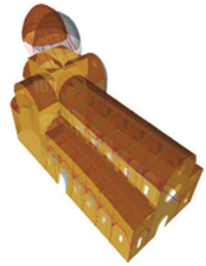
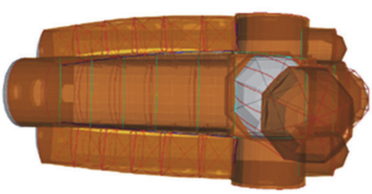
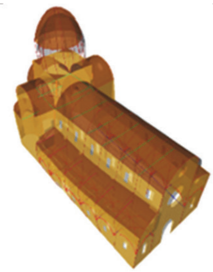


Figure 8. Changing the natural frequency values as function modulus of elasticity

For the sake of simplicity, the first three mode shapes were considered. From the updated numerical model, the corresponding mode shapes were determined (Table 3.).

Table 3. Numerically obtained mode shape of the cathedral for the corresponding experimentally obtained values of natural frequencies

Mode	Mode shape		Mode shape description
	Top view	3D view	
1			Bending around the X axis, symmetric
2			Bending around the X axis, antimetric
3			2.bending mode around X axis

The final value of the modulus of elasticity was determined as the mean value of the readings for each mode shape (Figure 9.). After the numerical model and its properties were obtained, the observed iron tie-rods of the updated global numerical model were subjected to axial tension (Table 2). Then, the global numerical model was subjected to seismic load according to EN 1998-1:2004 [14] and the values of the force in the tie rod were determined for this load case (Table 3).

Table 4. Values of forces and stress level in iron tie rod for the seismic actions in x and y direction

Tie rod	2B-C		3B-C		4B-C		5B-C	
Earthquake Direction	P_n [kN]	σ_n [MPa]	P_n [kN]	σ_n [MPa]	P_n [kN]	σ_n [MPa]	P_n [kN]	σ_n [MPa]
x	152.0	50.26	167.3	40.85	162.7	45.19	244.4	52.85
y	149.9	49.54	192.9	47.10	168.6	46.82	218.4	47.23
Tie rod	**6B-C**		**7B-C**		**7-8B**		**7-8C**	
Earthquake Direction	P_n [kN]	σ_n [MPa]	P_n [kN]	σ_n [MPa]	P_n [kN]	σ_n [MPa]	P_n [kN]	σ_n [MPa]
x	150.8	40.51	209.6	66.83	218.2	69.58	[kN]	70.39
y	164.0	44.06	214.9	68.53	223.8	71.35	259.9	72.18

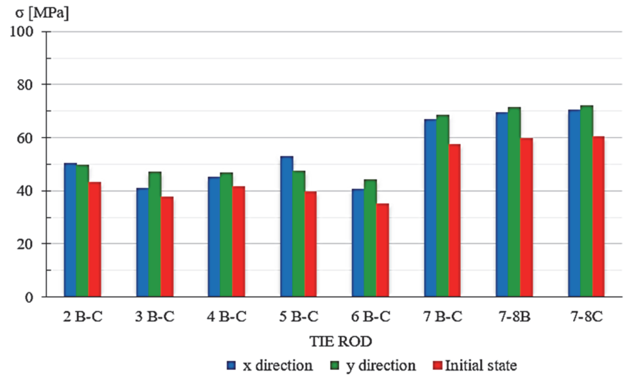


Figure 9. Comparison of stress level in iron tie-rods for the initial state and seismic actions in x and y-direction

4 Conclusion

Tie rods in historic buildings support masonry walls, buttresses, vaults, and arches to resist displacement. Consequently, they are subjected to axial tension and are in controlling horizontal forces and displacements caused by static and dynamic loads associated with seismic actions. The determination of these loads and the corresponding stress levels is very important. This paper presents a determination of axial forces and analysis of seismic actions on tie rods through a combination of experimental tests, numerical analysis and finite element model updating. Based on the experimental tests, model updating of local numerical model of tie rod and global model of structure, and numerical analysis, it can be concluded that due to the seismic action, the axial forces in the tie-rods increases (Figure 9.). Also, the bearing capacity of the observed tie rod should not be cancelled because the maximum stress value in the most loaded tie rod (tie rod 7-8C) is only 36.1% of the tensile strength of the cast steel.

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