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STIFFNESS CHANGES DUE TO STATIC LOADING OF A BRICK ARCH

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Abstract. *A brick arch was loaded under laboratory conditions in three successive loading steps. No cracks were observed but reduction of natural frequencies and stiffness of the arch was experimentally documented. The stiffness was evaluated in a non-destructive test using an impact hammer and only two accelerometers. The proposed identification technique based on known experimental modal analysis theory is tailored to stiffness evaluation of masonry vaults. The results and the applied method are extensively discussed.*

1 INTRODUCTION

Modal parameters reflect stiffness changes in building structures and are therefore applied in the framework of health monitoring, estimated in order to detect possible damage in structures or just to check the integrity of finite element models [1,2,3].

Application of experimental modal analysis to masonry structures (overview [4]) is less common than to bridges, but there are numerous tests of churches [5,6,7] and publications dedicated to the dynamic behaviour of masonry arches. The presented article follows up on investigations performed in the nighties in England [8,9,10] and applies similar approach as [11]. A good example of laboratory research appeared recently in [12].

Brittle materials that form cracks under static loading are more suitable to vibration based damage detection than steel structures or pre-stressed concrete. On the other hand, they are likely to behave in a non-linear way which makes the application of experimental modal analysis questionable. Experience with similar structures shows that the influence of non-linear effects (probably mainly due to damping) increases with distance from the excitation (loading) point, and the dynamic response of the structure depends on loading location [13].

The proposed experimental procedure therefore only uses measured driving point frequency response functions (FRF) for the evaluation of the condition of the investigated brick arch. It does not extract the modal properties but instead estimates the static flexibility from the FRFs directly. The experimentally obtained flexibility increases with applied static load as the measured response to the hammer impact confirmed.

The proposed method is therefore possibly applicable in the health monitoring of brick vaults as well as in the experimental assessment of the collapse mechanism of masonry arches.

2 STATIC FLEXIBILITY ESTIMATION

Flexibility (which is the inverse of stiffness) has been successfully applied for damage detection in the past [14]. The main advantage is that it converges early with the few first modes when derived from measured results.

Static flexibility can be estimated as the frequency response function (receptance) at zero frequency [8,15]. The FRF at each driving point can be approximated as the sum of as many single degrees of freedom (SDOF) systems as there are distinct frequency peaks in the particular FRF for each driving point independently.

The FRFs were obtained from hammer impacts, and the driving (hitting) points were selected at regular distances along the vault (see Fig.1) – 16 points along the arch. As it is impossible to measure the vibrations at the excitation point, two points to the left and right of it were selected. It was measured only in the direction perpendicular to the vault surface, and the two accelerometers were moved along with the hammer.

In order to estimate the FRFs at the zero frequency it is necessary to perform a curve fit and transfer the measured inertances into receptances. A good curve fit around the peaks is essential for the success of the method, however, a simple SDOF fitting worked fairly well here. The dominant peak frequencies were estimated from the summarized FRF, and then a simple amplitude fitting was performed. Application of more sophisticated fitting methods is planned next.

3 ANALYSIS

In order to check the credibility of the experimental results a linear finite element (FE) model was created in ANSYS 17.2 using Solid185 elements. First comparisons of the measured and computed results confirmed that the boundary conditions were close to the clamped state. After adjustment of the elasticity modulus to 3 GPa and the density to 1700 kg/m3 the natural frequencies roughly corresponded to the measured ones (see Tab.1). This model was used to compute the static deformations due to unitary static load at measured locations which correspond to the experimentally evaluated flexibilities (see Fig.3). Only the intact condition was simulated.

Table 1: Comparison of computed and measured natural frequencies for the intact condition

Mode No.	Analytical Frequencies [Hz]	Experimental Frequencies [Hz]
1	28,52	30,7
2	35,32	32,4
3	55,75	52,0

4 EXPERIMENT

The experimental site is shown in Figure 1. The radius of the arch was 1.625 m, its span was 3m and width 0.75m. Accelerations were measured with the transducers SKF CMSS 793L in two rows of measured points perpendicularly to the surface at equal distances of approximately 255 mm. The 8202 Brüel&Kjaer impact hammer was used to hit the surface of the arch between the measured points with a peak force of approximately 400 N. The sampling rate of 1 kHz was used and the time for each measurement point took cca 120 s including five impacts for averaging.

After the dynamic experiments on the intact arch the static force of 24, 36, 48 kN (x2) was applied in three successive steps at the 1/3 points. After each loading step dynamic impact measurements were repeated in the unloaded condition. Finally, the arch was destroyed by 2x129 kN total force (it was reinforced by CFR plates).

Figure 1: Experimental site (note the two moving accelerometers at the vault´s heel)

In spite of the fact that no cracks could be observed on the arches after the stage where 48 kN was applied, the shifts in frequency spectra (see Fig.2) and the evaluated flexibilities (see Fig.3) revealed a gradual loss of stiffness. This drop in stiffness was not confirmed however by the deformations measured during the static loading. The hypothetical explanation for this phenomenon may be a possible development of micro cracks.

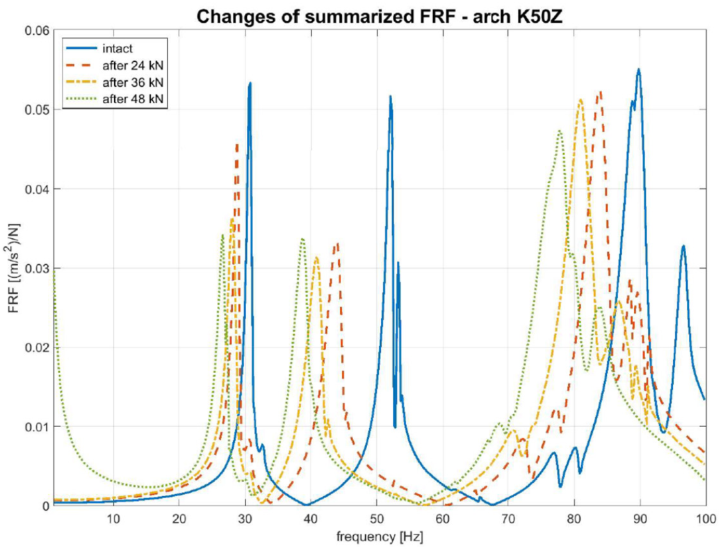

Figure 2: Summarized measured Frequency Response Functions

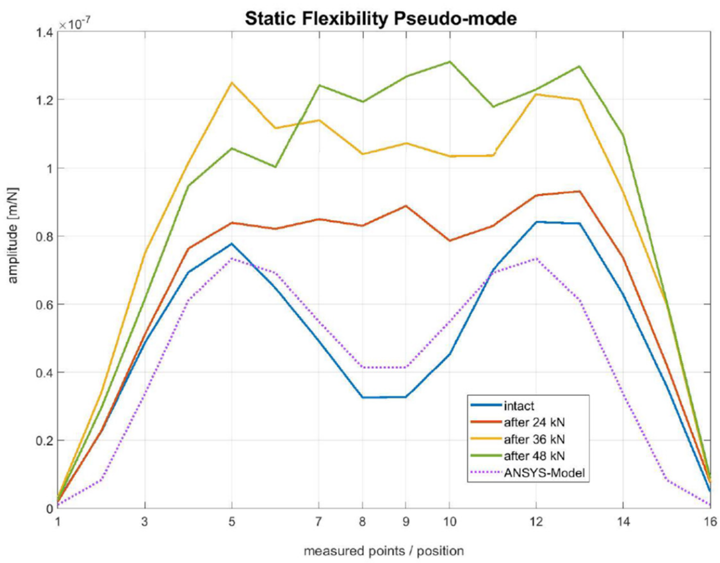

Figure 3: Experimentally estimated calculated flexibility

The increase in flexibility (or loss of stiffness) can be plotted relatively to the intact condition (see Fig.4) showing that the major damage occurred in the middle of the arch. This indicates that the experimentally estimated flexibilities could potentially be used to predict the failure mode which is sometimes a problem with ageing masonry structures, as mentioned in [10].

5 CONCLUSIONS AND DISCUSSION

The completed experiments showed that the dynamic properties of the tested masonry arch were influenced by the applied static load. The estimated flexibilities and the drop in natural frequencies indicate a gradual loss of arch stiffness due to the static loading. However, no significant drop in stiffness was observed during the static loading. A possible explanation may be that the behaviour of the arch at very low vibration levels (induced by the impact hammer) is influenced by micro cracking and is therefore of a different character than static behaviour under substantial static load.

The experimentally estimated flexibilities will therefore not be reliable in predicting static deformations of masonry structures – unlike steel structures [16] – but they could possibly be applied to predict failure modes after further research.

The tested arch was a bare structure without infill or permanent static loads, which made the dynamic testing easier. However, further application of the proposed procedure to test its applicability to the condition assessment of ageing masonry structures seems reasonable.

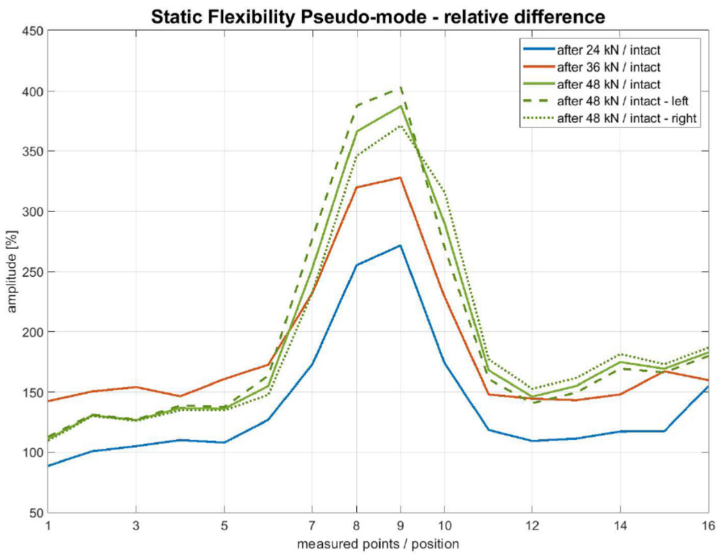

Figure 4: Relative Increase of Flexibility

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