Experimentally validated finite element models of two reinforced concrete beams subjected to surface-to-surface contact condition

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ABSTRACT

The prediction of vibration transmission in collapsed and fragmented reinforced-concrete buildings has the potential to inform decisions about the possibility to detect human survivors trapped in buildings after earthquakes by using structure-borne sound propagation. This paper focuses on the development and experimental validation of finite element models for two reinforced concrete beams subjected to surface-to-surface contact conditions. Finite element models of two free-free supported reinforced concrete beams were developed in Abaqus and validated against the results of experimental modal analysis. Predictions are shown for surface-to-surface contact between two beams and compared with experimental results in terms of eigenfrequencies and mode shapes.

Keywords: Finite Element Methods, Experimental Modal Analysis, Modal Assurance Criterion
I-INCE Classification of Subjects Number(s): 42, 75.3, 75.6

1. INTRODUCTION

The survival of trapped survivors in collapsed reinforced concrete buildings is affected by important variables including the structure type and void space formation, the cause of the structural collapse, the survival location in the building and the speed and sophistication of available search and rescue capabilities (1). This research forms part of a PhD project which is funded by the EPSRC and concerns an approach to search for human survivors using structure-borne sound propagation in collapsed and fragmented structures through the development, validation and use of theoretical models.

The aim of this paper is to investigate the contact conditions between two reinforced concrete beams when they form an X-shaped junction and assess whether it is feasible to model the dynamic behaviour of the junction using linear perturbation procedures. Experimental modal analysis is carried out on two reinforced concrete beams subjected to various support conditions and the results are used for the validation of finite element models.

2. EXPERIMENTAL WORK

2.1 Test specimens

The experimental samples consist of two reinforced concrete beams (C25/30, S500) with the same dimensions (2.4 m length, 0.2 m width and 0.3 m depth). The beams A and B are reinforced with four and eight longitudinal steel bars of 16 mm diameter, respectively. The transverse reinforcement of both beams consists of 8 mm diameter stirrups placed at 200 mm centres along the beams (see Figure 1).

Table 1 gives the weight of each reinforced concrete beam that was measured using a crane scale.

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Table 1 - Beam weights

Beam	Weight [Kg]
1	352.0
2	354.4

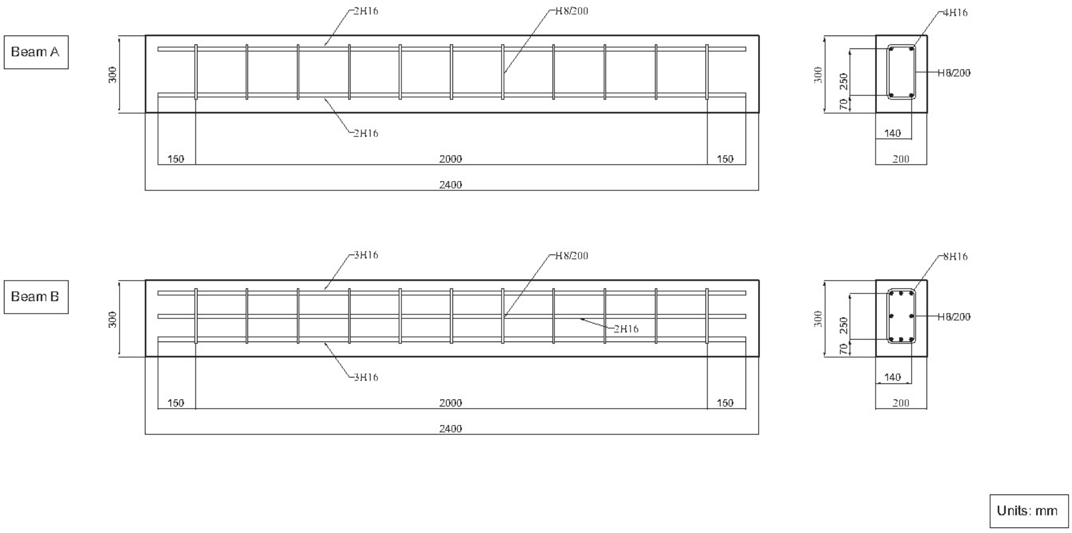


Figure 1 – Structural details of the reinforced concrete beams

2.2 Experimental setup

In test setup 1 (see Figure 2) the beams were suspended using polyester slings from an overhead crane in order to approximate a beam with free – free boundary conditions as the sling was assumed to have negligible effect on the dynamic response.

In test setup 2 (see Figure 3), square-section aluminum bars (25x25mm) supported beam A at each end to approximate simply supported conditions.

In test setup 3 (see Figure 4) an X-shape beam junction was formed after placing beam B on top of the configuration in setup 2. The angle between the two beams was 41.45°.

2.3 Experimental modal analysis

Experimental modal analysis was carried out to identify the eigenfrequencies and mode shapes of the three test setups. The beams were excited using an impact hammer (Brüel & Kjær Type 8200) and the response on the beams of setup 1 and 2 was measured using three accelerometers (Brüel & Kjær Type 4371). In setup 3, six accelerometers (Brüel & Kjær Type 4371) were used for measuring the accelerations (three on each beam). The transducers were connected to a FFT analyser (Brüel & Kjær Type 3050-A-060) via a Nexus Conditioning Amplifier (Brüel & Kjær Type 2692). The commercial software Brüel & Kjær Pulse Reflex was used for signal processing and the modal analysis. During the modal testing, the accelerometers remained at fixed positions whilst the impact hammer was moved along the excitation points.

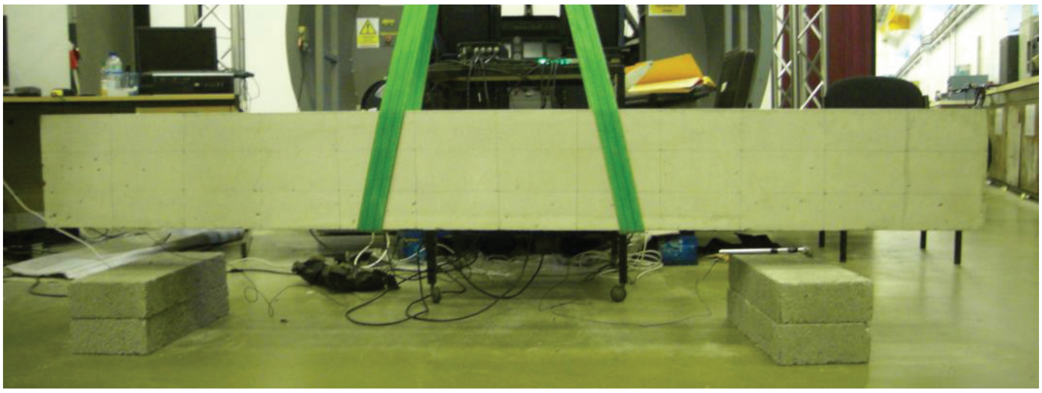


Figure 2 – Test setup 1 showing the test equipment and the polyester slings that approximate the free-free boundary condition for the beams

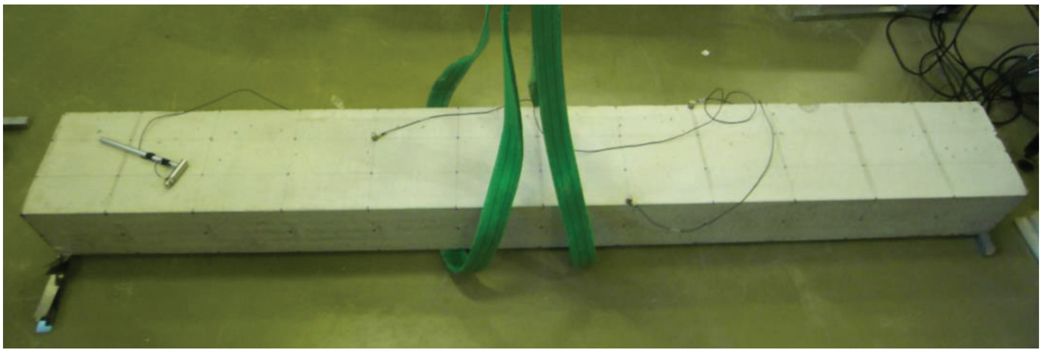


Figure 3 – Test setup 2 showing the transducers and the aluminium sections that approximate the simply support condition for the beam A

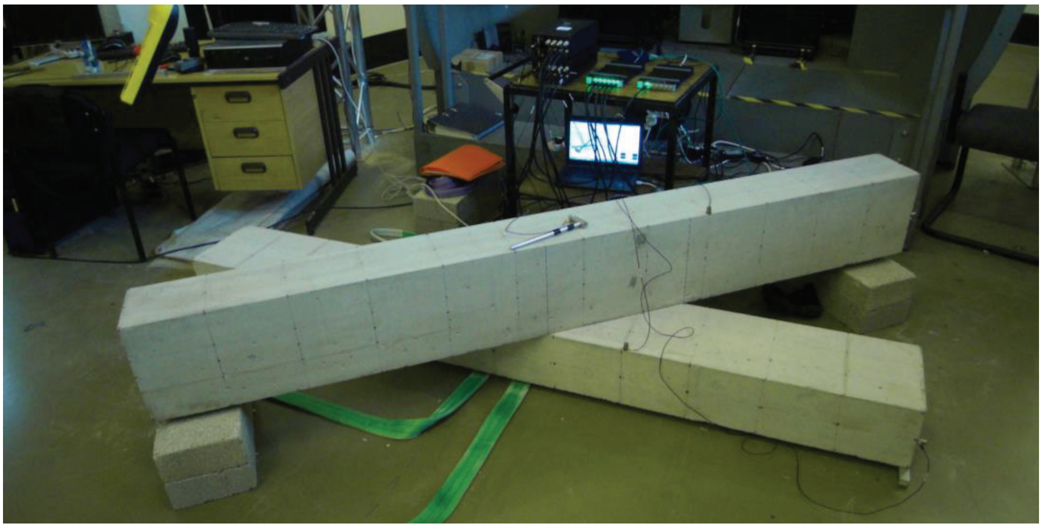


Figure 4 – Test setup 3 showing the test equipment and the X-shape junction formed by the beams A and B

3. FINITE ELEMENT MODELLING

3.1 Setup 1

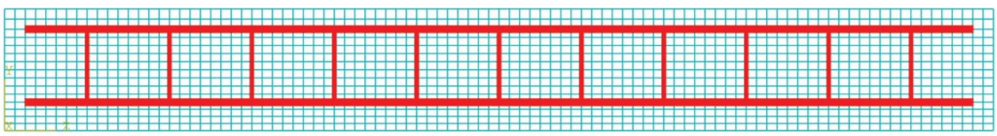
Finite element models of the two reinforced concrete beams were developed in Abaqus v6.14 (2) and eigenfrequency analysis was carried out to define their dynamic characteristics (eigenfrequencies and modeshapes). The solid element C3D20R (20 nodes) and the beam element B32 (3 nodes) were selected from the element library of Abaqus to model the concrete and the steel bars respectively (see Figure 5). Both elements were selected to have interpolation functions of the same order (quadratic) to avoid accuracy issues (3). A finite element mesh with dimensions of 25 mm in the longitudinal and 20 mm in the other two directions resulted in 27 elements per bending wavelength for the concrete and 8 elements per bending wavelength for the steel bars, at 3200 Hz. This mesh density fulfils the requirement for at least 6 quadratic elements per wavelength in structural and vibroacoustic problems (4).

Table 2 shows the physical and mechanical properties of the materials used in the models. The material properties of the steel and Poisson's ratio of the concrete were taken from the literature (5, 6). The density of the concrete for each beam was defined by dividing the weight of the beams by their volume after extracting the weight of the steel reinforcement.

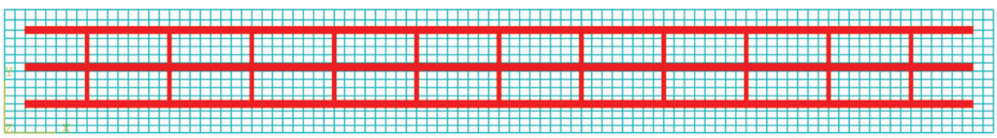
For each beam, the Young's modulus of the concrete, E_c was estimated after model updating against the experimental results. Numerical trials with different Young's modulus, E_c were carried out for beams A and B up to the stage where the first numerical eigenmode had 0% difference against the first experimental eigenmode in terms of eigenfrequencies. The estimated value of the Young's modulus for beam A is relatively higher than beam B but it is inside the range that is proposed in the literature for C25/30 concrete (7). A possible reason for this discrepancy might be that the two beams were cast on different days using different concrete mixture.

Table 2 – Material properties

Material	Density, ρ [Kg/m^3]		Young's modulus, E [N/m^2]	Poisson's ratio, v
Concrete	Beam A	2328.7	36875E06	0.2
	Beam B	2245.2	32475E06	
Steel	7800		200E09	0.3



Beam A



Beam B

Figure 5 – Finite element modelling of the reinforced concrete beams using solid and beam elements

3.2 Setup 2

The experimentally validated finite element model of beam A was rotated by 90 degrees to form the FEM model corresponding to test setup 2. The linear spring element, SPRING1 (indicated by purple markers in Figure 6) was selected from the element library of Abaqus to approximate the elastic support that the aluminium square bars provide to beam A. The stiffness, *k* of the springs was estimated equal to 1.128E06 N/m after model updating against the experimental results. Numerical trials with different spring stiffnesses were carried out up to the stage where the first eigenfrequency had 0% difference against the first experimental eigenfrequency.

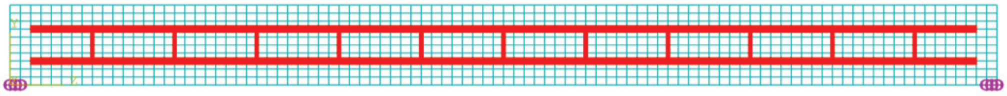


Figure 6 – Finite element model of setup 2

3.3 Setup 3

The experimentally validated finite element models of setup 2 and beam B were joined together to create the FEM model of the X-shape junction (Figure 7). The contact between the two beams was modelled using the general contact algorithm of Abaqus/Standard and was defined to have elastic normal and rough tangential behaviour. When a general contact is used in a linear perturbation step (such as in the eigenfrequency analysis) the contact remains "closed" during the analysis if it was closed at the beginning of it (2). Verification studies have shown that using a general contact with elastic normal behaviour during a linear perturbation step is equivalent to using an array of linear springs between the nodes of the two surfaces of the contact. The normal stiffness of the contact was estimated equal to 7308E06 (N/m)/m^2) after model updating.

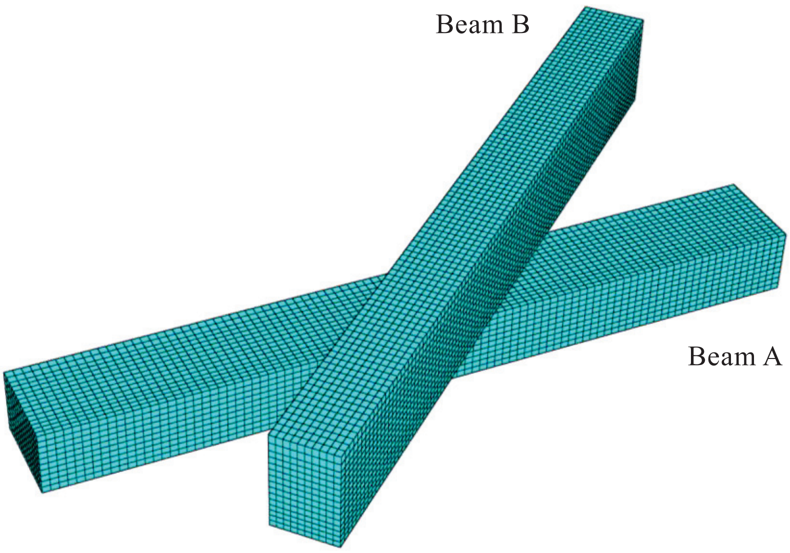


Figure 7 – Finite element model of the X-shape beam junction

4. RESULTS

4.1 Setup 1 & 2

For beams A and B (setup 1), close agreement was achieved between FEM and experimental eigenfrequencies as shown in Figure 8. For all the mode pairs in the frequency range from 1 to 3200 Hz, the percentage difference in eigenfrequencies was less than 4%.

Close agreement was achieved between FEM and experimental eigenfrequencies for beam A supported on aluminium square bars (setup 2) as indicated in Figure 8. For the majority of the mode pairs in the frequency range from 1 to 3200 Hz, the percentage difference was less than 4%. Only mode pairs 3, 5 and 6 show significant lower agreement with differences up to 34%.

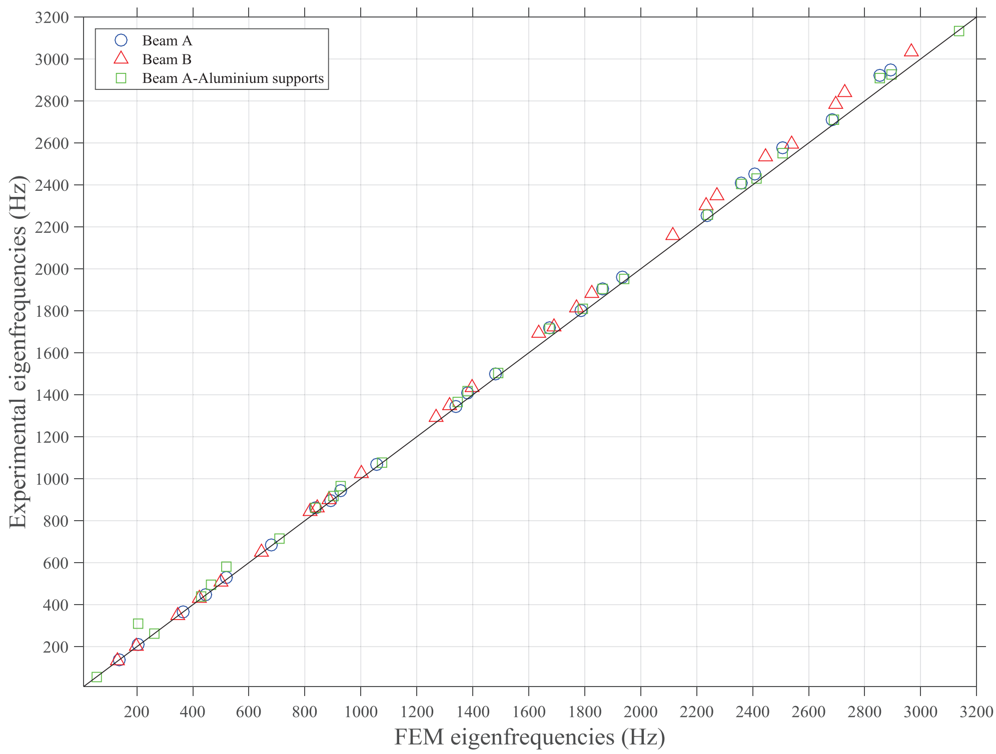


Figure 8 – Comparison between FEM and experimental eigenfrequencies for beams A, B (setup 1) and beam A supported on aluminium square bars (setup 2)

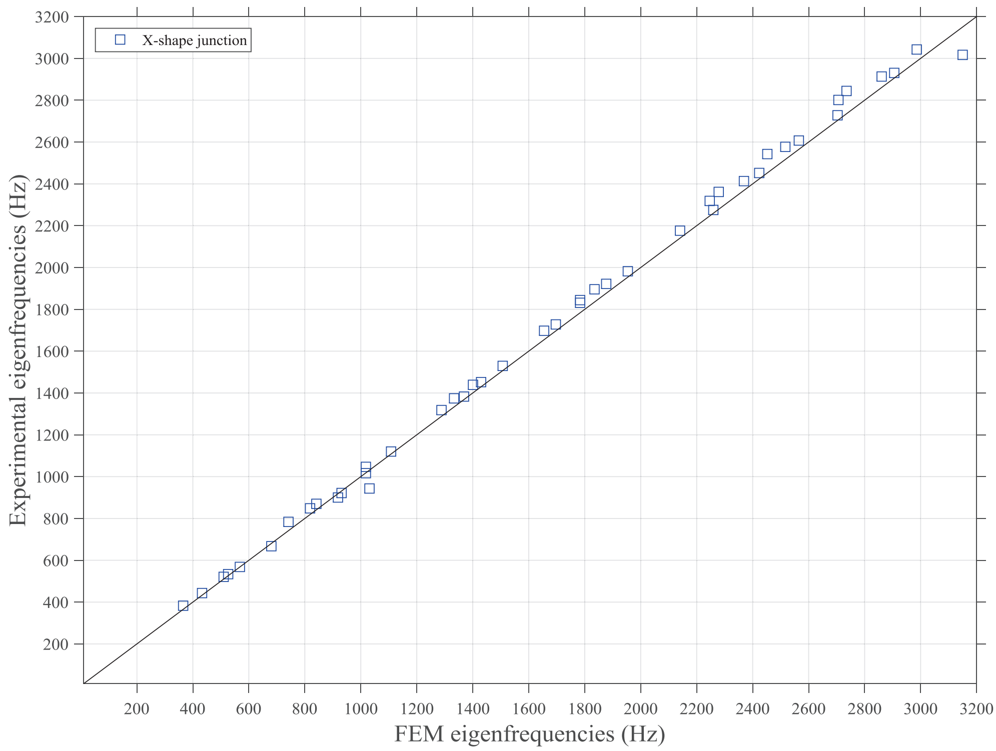


Figure 9 – Comparison between FEM and experimental eigenfrequencies for the X-shape beam junction (setup 3)

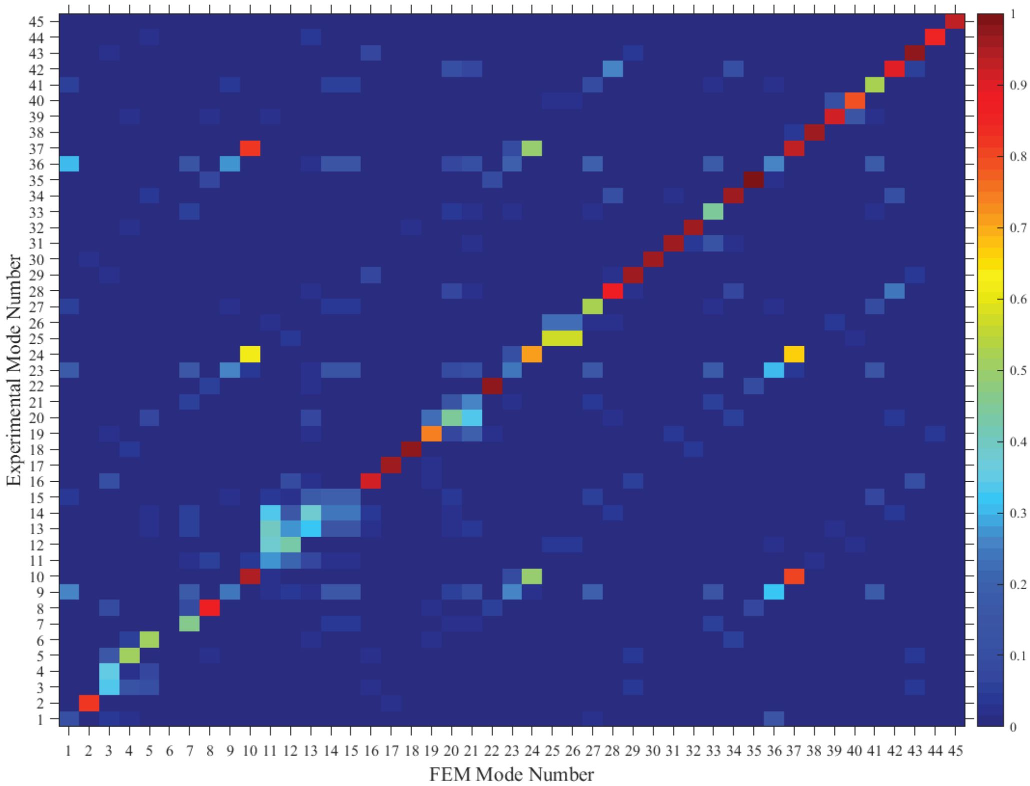


Figure 10 – MAC values for the X-shape junction (setup 3)

4.2 Setup 3

Close agreement was achieved between FEM and experimental eigenfrequencies for the X-shape junction, as shown in Figure 9. For all the mode pairs in the frequency range from 300 to 3200 Hz, the percentage difference in eigenfrequencies was less than 5%. Below 300 Hz, all the experimental modes were rigid body modes and were excluded from the validation procedure.

Figure 10 compares FEM and experimental results in terms of mode shapes using the Modal Assurance Criterion (MAC) (8). Above the 16th mode, adequate correlation was achieved for 21 mode pairs with MAC >0.71. Bellow the 16th mode, the agreement is significantly lower. That indicates that the FEM model is reliable in the frequency range from 1120 to 3200 Hz but not sufficient below 1120 Hz which requires further investigation.

5. CONCLUSIONS

Experimental work has quantified the material properties and the dynamic characteristics (i.e. eigenfrequencies and mode shapes) of two reinforced concrete beams. Finite element models were developed and successfully validated against the experimental eigenfrequencies with differences in eigenfrequencies of less than 4%. Further experimental work and finite element model updating has shown than the aluminium square bars provide an elastic support at both ends of beam A.

The dynamic characteristics of an X-shape junction of beams were assessed with experimental modal analysis which was used to validate the FEM model. Close agreement was achieved for 45 mode pairs in the frequency range from 300 to 3200 Hz with differences in eigenfrequencies of less than 5%. Above the 16th mode, adequate correlation was found for 21 mode pairs with MAC>0.71. Further investigation is needed to improve the agreement of the FEM model below the 16th mode.

The experimentally validated FEM model of the beam junction will be used at later stages of the research as a basis for assessing the potential to use statistical methods to model vibration transmission across fragmented structures.

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