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Vibration transmission across fractured beam-to-column junctions of reinforced concrete

Marios Filippoupolitis[1]
Acoustics Research Unit, School of Architecture, University of Liverpool
Liverpool, L69 7ZN, UK

Carl Hopkins[2]
Acoustics Research Unit, School of Architecture, University of Liverpool
Liverpool, L69 7ZN, UK

ABSTRACT

To detect human survivors trapped in buildings after earthquakes by using structure-borne sound it is necessary to have knowledge of vibration transmission in collapsed and fragmented reinforced-concrete buildings. In this paper, Statistical Energy Analysis (SEA) is used to model the vibration transmission in seismic damaged reinforced concrete beam-to-column junctions where the connection between the beam and the column is made only via the steel reinforcement. An ensemble of 30 randomly damaged beam-to-column junctions was generated using a Monte Carlo simulation with FEM. Experimental SEA (ESEA) is then considered with two or three subsystems to determine the Coupling Loss Factors (CLFs) between the beam and the column with either bending modes or the combination of all mode types. It is shown that bending modes dominate the dynamic response and that the uncertainty of predicting the CLFs using FEM with ESEA is sufficiently low that it should be feasible to estimate the coupling even when the exact angle between the beam and the column is unknown. In addition, the use of two rather than three subsystems for the junction significantly decreases the number of negative coupling loss factors with ESEA.

1. INTRODUCTION

Every few years an earthquake of high magnitude occurs around the globe resulting in collapsed structures with people trapped inside them. When victims are trapped inside a collapsed building, the challenge is to detect and locate survivors within a period that will allow them to be rescued. Most documented live rescues are accomplished within the first six days [1]. The prediction of vibration transmission in collapsed and fragmented reinforced-concrete buildings has the potential to inform decisions about the possibility to detect trapped human survivors by using structure-borne sound propagation. This research forms part of a funded project concerning 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.

[1] m.filippoupolitis@liverpool.ac.uk

[2] carl.hopkins@liverpool.ac.uk

The aim of this paper is to assess the potential to use Statistical Energy Analysis (SEA) to model vibration transmission in seismic damaged reinforced concrete beam-to-column junctions where the connection between the beam and the column is made only via the steel reinforcement. This is carried out using numerical experiments with Finite Element Methods (FEM) to create an ensemble of beam-to-column junctions for a Monte Carlo simulation which will allow use of Experimental SEA (ESEA) to determine Coupling Loss Factors (CLFs) between the beams. The two main aspects to investigate are (a) whether the number of the subsystems affects the validity and accuracy of FEM ESEA and (b) whether it is possible to only consider one type of wave motion (e.g. bending waves) or whether two or more types of wave motion could be considered simultaneously (e.g. bending and torsional waves).

2. METHODS

2.1. Finite Element Modelling

The junctions consist of a reinforced concrete beam (5.1 m length, 0.3 m width and 0.5 m depth) and a reinforced concrete column (8.0 m length, 0.4 m width and 0.3 m depth). The beam and the column are reinforced with six and eight longitudinal steel bars of 16 mm diameter, respectively and the transverse reinforcement consists of 8 mm diameter stirrups placed at 200 mm centres along the beams. To approximate seismic damaged junctions, a concrete discontinuity of 50 mm (measured horizontally at the narrowest point in Figure 1) was introduced between the beam and the column whilst the beam is rotated by an angle, θ and connected to the column via the longitudinal steel reinforcement (see Figure 1).

FEM modelling was carried out using Abaqus v6.14. The solid element C3D20R (20 nodes) and the beam element B32 (3 nodes) were selected from the element library of Abaqus [2] to model the concrete and the steel bars, respectively. The mesh density fulfils the requirement for at least six elements per wavelength [3] at frequencies up to 3200 Hz. Both the beam and the column were assumed to be simply supported at the ends.

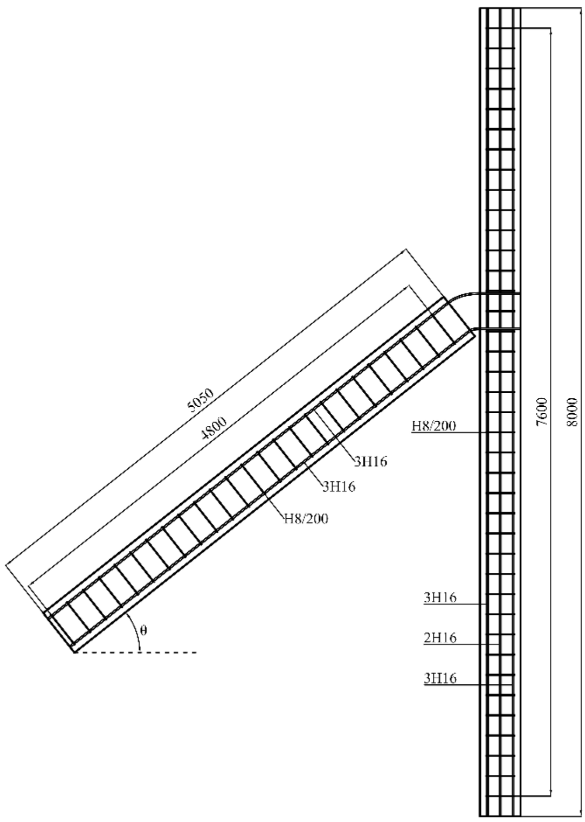

Figure 1: Geometry and reinforcement details of a damaged beam-to-column junction (units: millimeters).

Table 1 shows the physical and mechanical properties of the materials used in the FEM model [4]. The critical damping, ζ, was set to be equal to 0.05.

Table 1: Material properties

Material	**Density, ρ [kg/m^3]**	**Young's modulus, E [N/m^2]**	**Poisson's ratio, ν [-]**
Concrete	2287	34.7E09	0.2
Steel	7800	200E09	0.3

Mode-based steady-state dynamic analysis was used to calculate the dynamic response of the junctions up to 3200 Hz considering either only the out-of-plane bending modes or the combination of all modes. Results are shown for 16 frequency bands with a bandwidth of 200 Hz in the frequency range from 1 to 3200 Hz.

2.2. Monte Carlo simulation for ESEA

A sample of 30 damaged beam-to-column junctions was created using a Monte Carlo simulation with FEM. Although the angle between the beam and the column in a damaged junction is often between 45° and 55° [5] in this paper the angle, θ, (see Figure 1) was sampled from a uniform distribution θ~U(-80,80) to include more extreme angles in the ensemble and assess whether there was a significant variation with angle.

2.3. Experimental Statistical Energy Analysis (ESEA)

When two subsystems are considered, each beam and column of the junction represents a single subsystem (see Figure 2). When three subsystems are considered, the beam represents one subsystem but the column is divided into two subsystems as indicated in Figure 2. The output from the FEM models was used to calculate the subsystem energy and power input that would apply to an SEA model for each beam-to-column junction. These FEM data were then used in ESEA to determine coupling loss factors. The beam and the column of the junctions were excited using rain-on-the roof excitation at all the nodes of the surfaces which are indicated in Figure 2 with red lines.

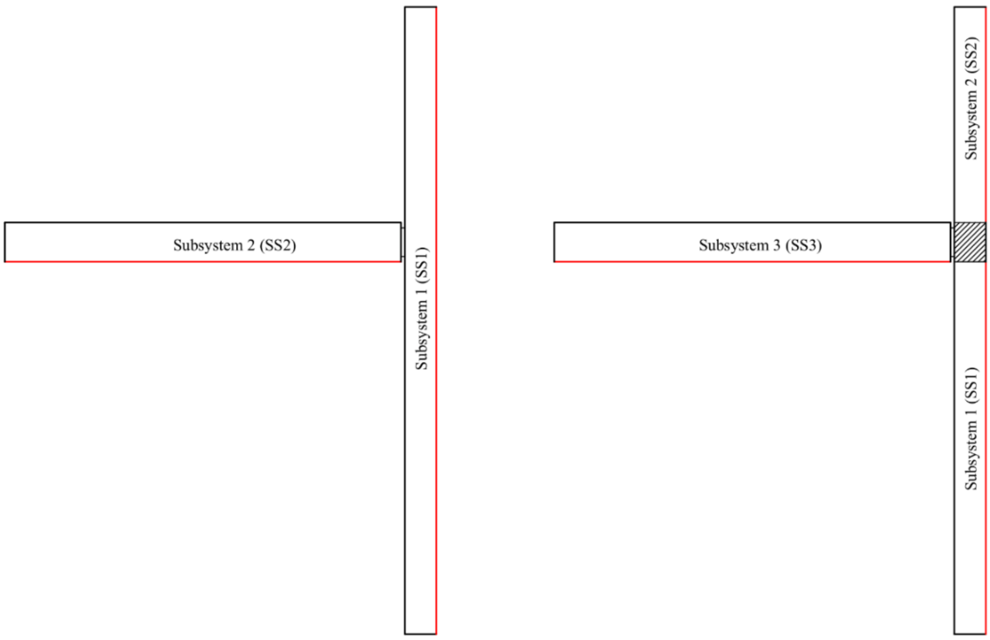

Figure 2: Division of the beam-to-column junctions in: (a) two and (b) three ESEA subsystems. The red lines indicate the surfaces where the rain-on-the-roof excitation is applied and the response is measured.

The ESEA matrix solution for two and three subsystems is given by the following equations (6):

$$\begin{bmatrix} \sum_{n=1}^{2}\eta_{1n} & -\eta_{21} \\ -\eta_{12} & \sum_{n=1}^{2}\eta_{2n} \end{bmatrix} \begin{bmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{bmatrix} = \begin{bmatrix} \frac{W_{\mathrm{in}(1)}}{\omega} & 0 \\ 0 & \frac{W_{\mathrm{in}(2)}}{\omega} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \sum_{n=1}^{3}\eta_{1n} & -\eta_{21} & -\eta_{31} \\ -\eta_{12} & \sum_{n=1}^{3}\eta_{2n} & -\eta_{32} \\ -\eta_{13} & -\eta_{23} & \sum_{n=1}^{3}\eta_{3n} \end{bmatrix} \begin{bmatrix} E_{11} & E_{12} & E_{13} \\ E_{21} & E_{22} & E_{23} \\ E_{31} & E_{32} & E_{33} \end{bmatrix} = \begin{bmatrix} \frac{W_{\mathrm{in}(1)}}{\omega} & 0 & 0 \\ 0 & \frac{W_{\mathrm{in}(2)}}{\omega} & 0 \\ 0 & 0 & \frac{W_{\mathrm{in}(3)}}{\omega} \end{bmatrix} \tag{2}$$

where η_{ij} is the coupling loss factor from subsystem i to j, η_{ii} is the internal loss factor for subsystem i and E_{ij} is the energy of subsystem i when the power is input into subsystem j, $W_{\mathrm{in}(i)}$ is the power injected into subsystem i, and ω is the angular frequency.
The energy associated with each subsystem is given by (6)

$$E = m\langle v^2\rangle_{t,s} \tag{3}$$

where m is the mass of the subsystem and $<v^2>_{t,s}$ is the temporal and spatial average of the mean-square velocity of all the unconstrained nodes of the subsystem.
For rain-on-the-roof excitation at P nodes, the power input, W_{in} is given by (6)

$$W_{\mathrm{in}} = \frac{\omega}{2}\sum_{p=1}^{P}\left(\mathrm{Im}\{\hat{F}\}Re\{\hat{w}\} - \mathrm{Re}\{\hat{F}\}Im\{\hat{w}\}\right)_p \tag{4}$$

where F is the force and $\hat{w}$ is the peak out-of-plane displacement associated with each node.

3. RESULTS

3.1. Coupling loss factors from FEM ESEA with two subsystems

Figure 3 compares the coupling loss factors η_{12} and η_{21} from FEM ESEA with two subsystems, considering only bending modes or the combination of all modes in the frequency range from 1 to 3200 Hz. The FEM ESEA results for the 30 damaged beam-to-column junctions are shown in terms of a mean value with 95% confidence intervals.

The comparison of the CLFs from FEM ESEA with bending modes and the combination of all modes showed close agreement (differences within 5 dB) from 100 to 2500 Hz. Above 2500 Hz, the differences were up to 10 dB. The 95% confidence intervals for the damaged junctions show that the uncertainty is sufficiently low that it should be feasible to estimate the coupling even when the exact angle between the beam and the column is unknown in the damaged junctions of a real collapsed building.

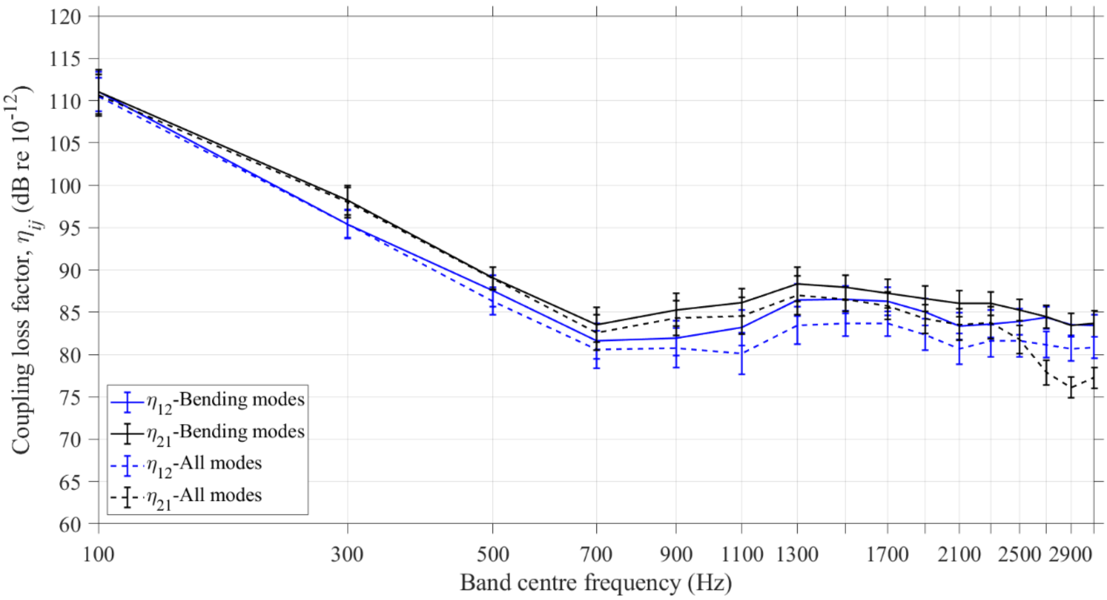

Figure 3: Coupling loss factors η_{12} and η_{21} resulted from FEM ESEA with two subsystems with bending only and the combination of all modes. The error bars denote the 95% confidence intervals.

For consideration of only bending modes or the combination of all modes, FEM ESEA resulted in positive CLFs for each of the 30 damaged junctions except for one junction in the frequency band of 100 Hz as indicated in Figure 4.

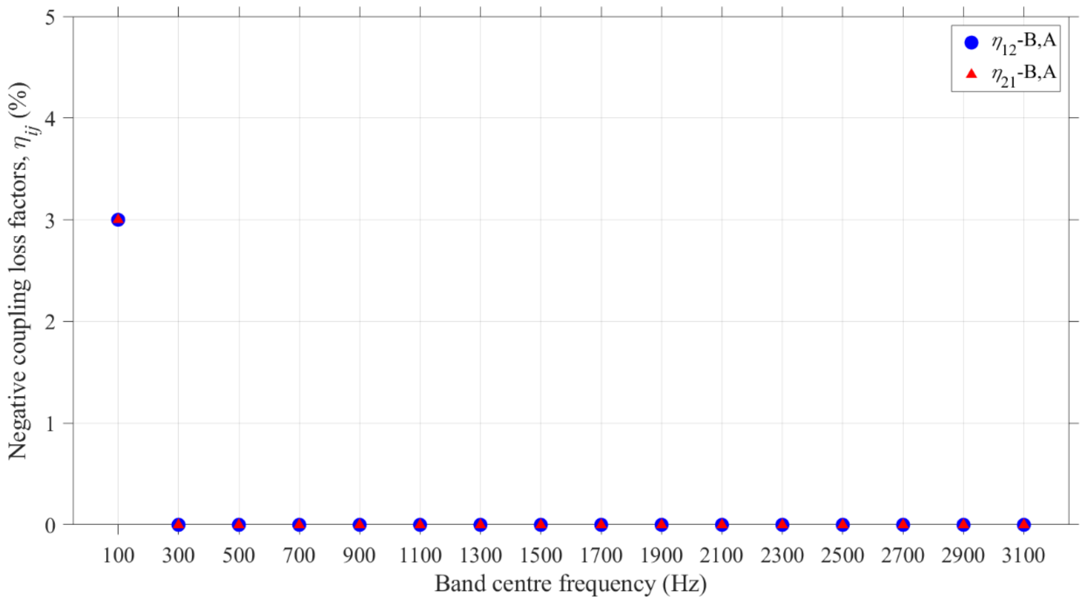

Figure 4: Percentage of negative CLFs η_{12} and η_{21} resulted from FEM ESEA with two subsystems with bending only (B) and the combination of all modes (A).

3.2. Coupling loss factors from FEM ESEA with three subsystems

Figures 5 to 7 allow comparison of the coupling loss factors from FEM ESEA with three subsystems, considering either bending or combination of all modes in the frequency range from 1 to 3200 Hz. The FEM ESEA results for the 30 damaged beam-to-column junctions are shown in terms of a mean value with 95% confidence intervals. The differences between the CLFs from the FEM ESEA for bending only and the combination of all modes were up to 5 dB between 100 and 2500 Hz. Above 2500 Hz, the differences were between 5 and 10 dB. The 95% confidence intervals show that the uncertainty is sufficiently low that it should be feasible to estimate the coupling even when the exact angle between the beam and the column is unknown in the damaged junction of a real collapsed building.

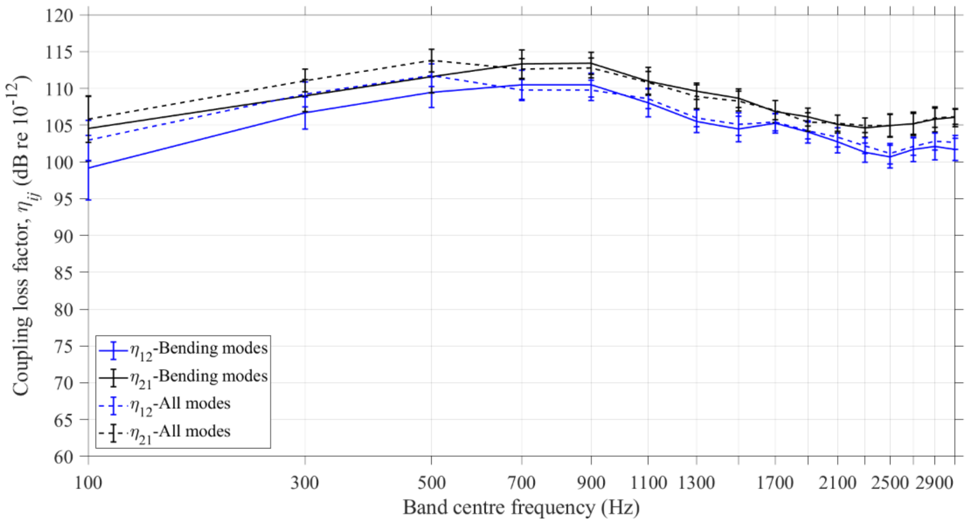

Figure 5: Coupling loss factors η_{12} and η_{21} resulted from FEM ESEA with three subsystems with bending only and the combination of all modes. The error bars denote the 95% confidence intervals.

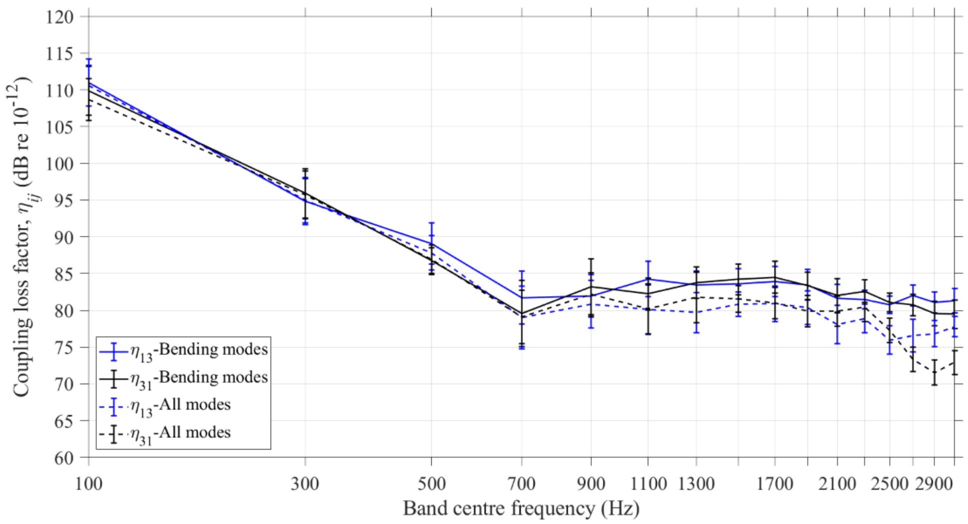

Figure 6: Coupling loss factors η_{13} and η_{31} resulted from FEM ESEA with three subsystems with bending only and the combination of all modes. The error bars denote the 95% confidence intervals.

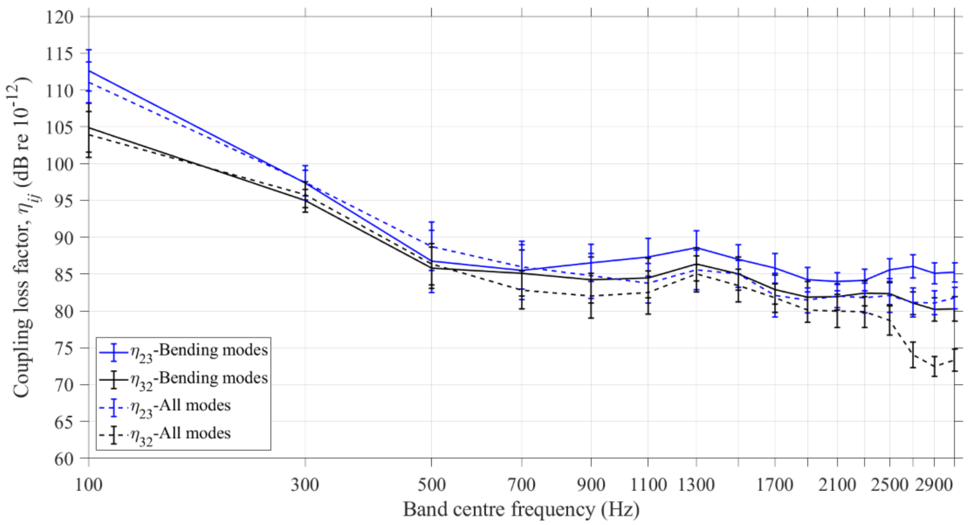

Figure 7: Coupling loss factors η_{23} and η_{32} resulted from FEM ESEA with three subsystems with bending only and the combination of all modes. The error bars denote the 95% confidence intervals.

Regardless of the type of modes (bending or combination of all modes), the consideration of three subsystems for the FEM ESEA of the 30 damaged beam-to-column junctions resulted in a significant number of negative coupling loss factors (see Figures 8 and 9). Specifically, below 1500 Hz the percentage of the junctions with negative loss factors was between 17 and 54%. These mainly occurred with the CLFs from the column (SS1 and SS2) to the beam (SS3) and vice versa. Above 1500 Hz, the percentage of the junctions with negative loss factors was between 3 and 10%.

Comparing the above percentages with the 3% of negative CLFs of Figure 4 (FEM ESEA with two subsystems), it is seen that in damaged junctions the use of two instead of three subsystems in FEM ESEA significantly decreases the number of negative coupling loss factors.

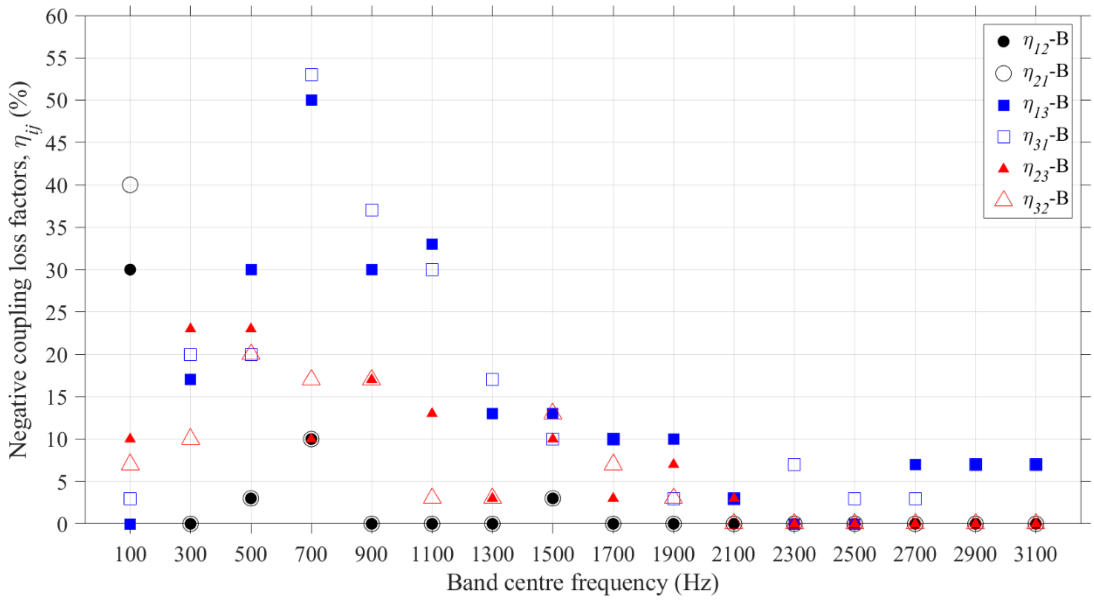

Figure 8: Percentage of negative CLFs resulted from FEM ESEA with three subsystems with bending modes only (B).

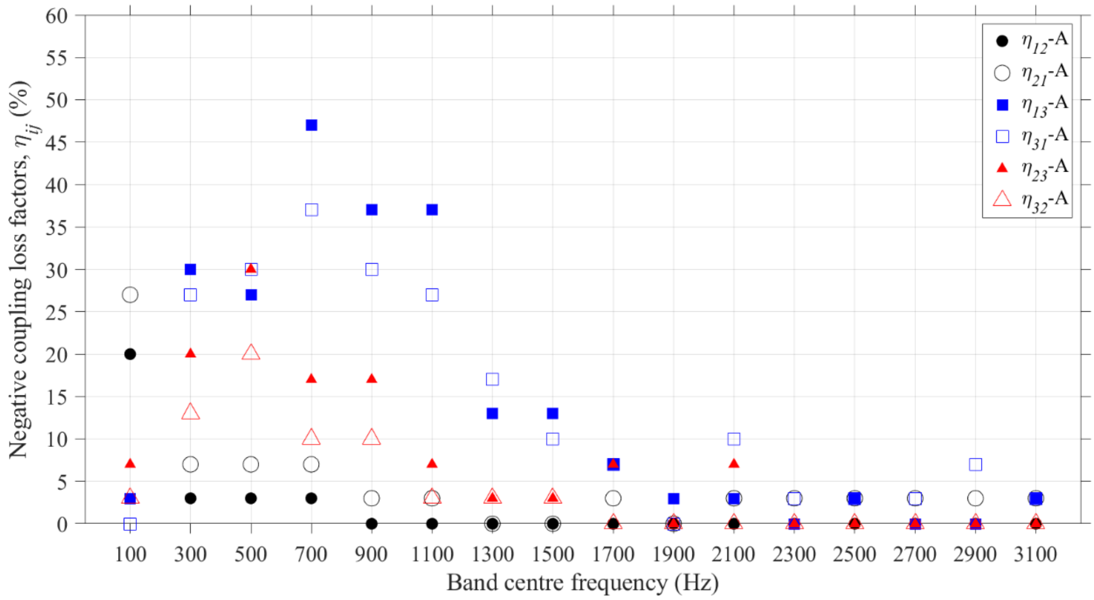

Figure 9: Percentage of negative CLFs resulted from FEM ESEA with three subsystems with the combination of all modes (A).

4. CONCLUSIONS

An ensemble of 30 randomly damaged beam-to-column junctions was generated using Monte Carlo simulation with FEM that allowed ESEA with two or three subsystems to be used to determine the CLFs between the beam and the column considering either only bending or the combination of all modes.

Regardless of the number of the subsystems, the CLFs from FEM ESEA were similar with only bending and the combination of all modes. This indicated that the bending modes are dominating the dynamic response of a beam-to-column junction over the combination of all the modes when the beam is connected to the column only via the steel reinforcement.

It was shown that the uncertainty in predicting the CLFs using FEM ESEA is sufficiently low that it should be feasible to estimate the coupling even when the exact angle between the beam and the column is unknown. In addition, the use of two instead of three subsystems should be preferred in FEM ESEA since it significantly decreases the number of negative coupling loss factors.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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