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Numerical simulation round robin of a coupled volume case: Preliminary results

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Abstract

The advantages and limitations of most numerical methods in room acoustics have to date been primarily evaluated in single-volume room conditions, placing emphasis on early reflection components and the early part of the room acoustic impulse response. Few studies have examined the capabilities of simulations to model correctly the case of coupled volumes, where the late part of the impulse response is not a simple extension of the early part and needs to be accurately represented. This work presents preliminary results of a round robin study comparing numerical simulation results with coupled volume theory, using physical scale model measurements to define general parameters. Numerical methods included geometrical acoustic solutions, with image source method and ray/cone/path-tracing type approaches, and wave-based methods, comprising several FDTD implementations. A scale model was used to set the parameters of a statistical model to ensure a physically realistic configuration. Room model coordinates were specified. To avoid issues regarding variations in implementation of material and scattering behaviors across methods, the reverberation time of separate individual volumes was prescribed in the uncoupled condition. Volumes were then coupled and the results analyzed. The comparison is of a rather simplified room acoustic model, assuming homogeneous boundary conditions.

Keywords: Room acoustics, Coupled volume system

1 INTRODUCTION

A system of coupled volumes consists of two or more spaces that are connected through an acoustically transparent opening. When a main room containing the source is coupled with a more reverberant auxiliary volume, the sound decay within the main volume can exhibit a non-exponential behavior. During the last decades, numerous new construction concert halls and other performing art spaces have had coupled volumes integrated in their design. They offer various advantages like providing high perceived levels of clarity and reverberation at the same time, two qualities that are usually contradictory in single volume spaces. In addition, coupled volumes are found in other situations, such as stage houses and stair wells. As such, an evaluation of the ability of current numerical methods to model them sufficiently correct for a given purpose is of interest.

Three round robin type studies on room acoustical numerical simulations have been conducted between 1994 and 2002 [1, 2, 3, 4] which compared the results of different algorithms with measurements in single volume spaces. The procedure followed was close to that encountered in acoustic planning in the field of building design and construction. First the acoustic materials were either described, later the acoustic properties of the materials were prescribed according to measurements or data tables for uniformity. These studies have highlighted some trends between simulation tools, while also showing the importance of user variability and input data quality. Comparing results obtained by novice or insufficiently-trained users, or using general data for specific materials both lead to higher variances and poor matching to measured results.

In order to assess the capability of different room acoustic simulation tools to accurately predict the acoustics of coupled volumes, the protocol employed in the present work aims to minimize the variance due to input and user variables. For this first comparison, a very simplified architecture is employed. Based on a physical scale model configuration of a simple shoebox-type coupled volume system composed of two rooms (a main room and a single reverberation chamber) linked by a single large aperture, basic acoustic measurements are carried out separately for the two volumes in isolation to determine the equivalent homogeneous acoustic material properties. In order to avoid issues regarding variations in implementation of material definitions and scattering behaviors across different methods, participants were asked to fit their boundary conditions in each room according to the measured reverberation times in the uncoupled configuration. Identical geometrical data, corresponding to the wall geometries of the scale model, transformed to 1:1 scale, and the uncoupled acoustic parameters of the two volumes were provided. Participants were comprised principally of the developers of the tested software, so that error effects due to users was limited. To simplify the task of model calibration and as a compromise between geometrical and wave-based methods, this study was limited to the 1 kHz-octave band.

2 MODELS AND METHODS

2.1 Coupled volume theory

A statistical-acoustics model of energy decay in a system of two coupled volumes [5, 6]. These models are based on diffuse-field theory assumptions, that reverberant energy within each volume decays exponentially, as described by Sabine's model, and rooms interact through the exchange of diffuse energy. These models lead to the resolution of a system of ordinary differential equations. This system for N rooms can be written as:

$$V_i \frac{dE_i}{dt} = -\frac{cA_iE_i}{4} + \sum_{j=1, j\neq i}^{N} \frac{cS_{ij}(E_i - E_j)}{4} \tag{1}$$

where $i = 1, \ldots, N$, c is the speed of sound, E_i denotes the average energy density in the ith room, V_i is the volume of the ith room, and A_i is the equivalent absorption of the ith room calculated according to Sabine's model as $S_i\bar{\alpha}_i$, where S_i and $\bar{\alpha}_i$ are the total surface area and the averaged absorption coefficient of the ith room, respectively. The coupling area between room i and an adjacent room j is denoted S_{ij}. The resulting system of linear differential equations (Eq. 1) can be presented in matrix form and solved by finding the corresponding eigenvalues and eigenvectors, determining the constant terms from initial conditions.

2.2 Scale model and measurements

To ensure the tested simplified configuration represents a physically realisable system, a scale model was employed to obtain the basic parameters. Subsequent studies may rely on more detailed geometrical models with the inclusion of specific material properties (absorption & scattering coefficients determined via direct laboratory measurements). Such details could affect local variations in the simulated field across positions, as well as early reflection patterns and possible flutter echoes when absorption and scattering are low and unevenly distributed.

The scale model is a very schematic coupled volume system representing the dimensions of a 1:20 scale concert hall (Fig. 1). It is composed of two rooms: a large box with its walls covered with diffusive and lightly absorptive materials and a smaller box with hard reflective materials to have a more reverberant cavity. They represent a main room and a reverberation chamber of 17 000 m^3 and 5400 m^3 at full scale, respectively. The two volumes are acoustically linked by a common wall which contains a single aperture whose surface area is ≈1 % of the total surface area of the main room's walls. The side and rear walls are slightly tilted by an angle of 2° in each room to avoid flutter echoes occurring between parallel surfaces in such simplified shoebox-shaped volumes. The main room is currently sparse, and the inhomogeneous material distribution is evident. A schematic representation of the coupled room system and photo of the main room are shown in Fig. 1, also indicating the prescribed source (2) and receiver (4) positions. Sources and receivers were considered to be omnidirectional for the purposes of this study. This model has been used in previous studies [7, 8, 9], though the exact configuration of the main room and its materials has been changed from those studies.

Measurements were conducted with a miniature dodecahedral loudspeaker (Dr-Three 3D-032) as a sound source driven by an amplifier (Samson Servo 120a) with several microphone receivers (DPA 4060). All were connected to an audio interface (RME Fireface 800) configured at a sample rate of 192 kHz and controlled via MATLAB 2018b. The exponential swept-sine technique was used to obtain the room impulse responses. Fre-

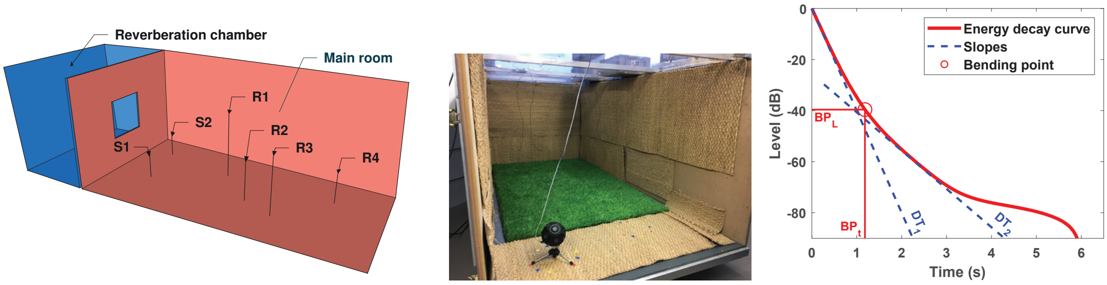

Figure 1. (left) Schematic view of the coupled volume model. (center) Photo of the main room of the scale model. (right) Definition of acoustical parameters adapted to double-slope energy decay curves.

quencies spanned 200 Hz to 60 kHz, covering the octave band of interest centered on 1 kHz at full scale.

2.3 Analysis and quantification

Several quantifiers and methods have been proposed to described non-exponential decays [10]. The quantification method used in this study to analyze decay curves derived from Schroeder's backwards integration method, obtained in the measurements and in the simulations, is called the *Marching Line* [7]. It is based on a direct comparison between the decay curve and linear regressions. It provides the number of slopes with equivalent decay rates, and the time & level of bending points between two consecutive slopes. To describe such a decay curve with two slopes, the employed parameters are the equivalent reverberation times DT_1 and DT_2 of the first and second slope, respectively, and the coordinates of the bending point in time BP_t and level BP_L (see Fig. 1).

2.4 Entries

Solicitations for participants in this study was done via requests over email to a number of persons involved in the research, development, or use of room acoustics simulations. They were provided with all the geometrical data needed for the construction of the 3D model, as well as the instructions concerning the calibration procedure based on the uncoupled acoustic parameters. In total, there were 11 different entries using 10 different numerical methods with 3 wave-based methods, and 7 geometrical acoustic implementations. A short description of the programs used, mostly provided by participants, and their parameters are presented in arbitrary order.

I-Simpa: Version 1.3.4 is an open-source graphical user interface developed to host three-dimensional numerical codes for the modeling of sound propagation in complex geometrical domains. The calculation code used was SPPS (from French *"Simulation de la Propagation de Particules Sonores"*), version 2.2.1, based on a particle-tracing method [11]. The radius of the receivers was set to 10 cm, 50 million particles were used for each source and were collected using time slots of 20 ms.[1]

Wave-based: Two academic participants used CE-FDTD methods with different schemes. One used an implementation of the 3D standard rectilinear scheme, known as standard leapfrog scheme (SLF) [12] while the other used the interpolated wideband (IWB) scheme [13]. The SLF scheme used a $c = 344\,\mathrm{m\,s^{-1}}$, $f_s = 18\,933\,\mathrm{Hz}$, a spatial grid of 31.5 mm and $\Delta t = 52.82\,\mu\mathrm{s}$. The IWB scheme used $c = 340\,\mathrm{m\,s^{-1}}$, spatial grid of 8.5 mm, and $\Delta t = 23.75\,\mu\mathrm{s}$. The room surface boundaries were assigned to be locally reacting and the impedance is frequency-independent in both implementations. A third entry used a software developed at the University of Edinburgh based on the hybrid FDTD/FVTD method described in [14].

RAMSETE: Version 3.02 uses a Pyramid Tracing algorithm capable of solving the sound propagation problems in large enclosures or outdoors [15]. The method employed was pyramid tracing with surface scattering and edge diffraction up to the second order. Discrete paths were saved up to fourth order. The number of pyramidal

[1]The resulting data were echograms, not impulse responses. In consequence, no 1 kHz-octave band filter was applied.

beams launched by each source was 32 768 and the energetic impulse responses were computed with a resolution of 1 ms.

CATT-Acoustic: TUCT v2.0e:1.01 algorithm 1 [16] was used. Ray split-up between diffuse and specular reflections are performed randomly with a probability determined by the scattering coefficient (max split-order= 0). Calibration of the main room used 716 486 rays, the reverberation chamber 638 082 rays, for each source. The coupled configuration used 2 000 000 rays with auto-edge scattering applied on the aperture edge planes.

ODEON: Simulations were performed using ODEON Combined version 15.13 [17]. The calculation model is hybrid, using image source method plus radiosity for early reflections and ray tracing plus radiosity for late reflections. Reflections of first and second order were treated as early reflections. A total of 16 000 rays were used for late reflections for each source. Ray tracing was made using the method of reflection based scattering.

RAVEN: The Room Acoustics for Virtual ENvironnements software, developed at RTWH Aachen University [18, 19], uses a hybrid algorithm that combines Image Source Method for the direct sound and early reflections with ray-tracing for the late reverberation, with ray tracing calculating an energy decay histogram based on specular reflections of order ≥ 3, diffuse reflections for order ≥ 1, and diffuse energy based on the diffuse rain model. One participant used the 2018.v2 version with 500 000 rays for the calibration of the absorption coefficients and 1 000 000 rays for the coupled rooms simulations. A second entry used 2019.v1 version with 500 000 rays for all simulations. They both used image sources for specular reflections up to the second order and ray-tracing parameters set to 1 m for the radius of the detection sphere with time slots of 10 ms.

Path tracing: One entry employed a geometrical acoustics simulation method based on unidirectional path tracing from the receiver position with next event estimation, a computer graphics method of rendering images of three-dimensional scenes, also termed “diffuse rain" in acoustics [18]. Materials are described by a glossy Phong reflectance model that is controlled by the scattering coefficient. Energy decay histograms are computed for each band at full sample rate, converted to pressure envelopes, then the per-band pressure envelopes are multiplied by filtered white noise and summed to compute the pressure IR.

SoundPLANnoise: Version 8.2 using the Sound Particle Diffraction method [20] was used. It incorporates specular and diffuse reflections, transmission, room scattering, and geometrical diffraction. Diffuse reflections are modeled according to the Lambert cosine law and diffraction is performed according to the uncertainty-based diffraction theory [21], which allows for arbitrary diffraction orders. The energetic impulse responses were computed with a resolution of 1 ms.[2]

The main room has a large surface area of diffusing materials (characteristic roughness depth of 6 cm at full scale, while the second room has smooth walls. For the 1 kHz band, scattering coefficients of 20 % and 10 % were suggested for the two rooms respectively. However, due to differences in implementations of such parameters, this was not a controlled parameter. For example, in the wave-based methods, one participant modelled wall roughness directly with a diffuser design.

Participants were asked to submit simulated room impulse responses in audio WAV format in order to apply the same routine for acoustical parameter calculations and thus avoid introducing another source of divergence from different implementations [22]. In the following results section, entries have been randomly assigned identification letters from A to K, to ensure anonymity.

3 RESULTS

3.1 Calibration of numerical models

In order to avoid issues regarding different implementations of absorption and impedance conditions across numerical methods, the reverberation time in each room was prescribed according to scale model measurements in the uncoupled configuration. For simplicity, participants were instructed to adjust material properties of walls uniformly for each room (*i.e.* all walls of each volume have the same material definitions) to match the prescribed reverberation times. Measurements and simulations were carried out for 2 source and 2 receiver posi-

[2] The resulting data were echograms, not impulse responses. In consequence, no 1 kHz-octave band filter was applied.

tions in the reverberation chamber and 2 source and 4 receiver positions in the main room. Measured impulse responses were numerically compensated for scaled air attenuation in the scale model. Prescribed average T_{30} in the main room and the reverberation chamber was 1.26 ± 0.064 s and 4.52 ± 0.065 s, respectively.

Figure 2 shows the reverberation times T_{30} for each source-receiver pair calculated from measured and simulated RIRs. For both rooms, the highest relative difference is 11 %. Overall, the calibration procedure was respected. The variances of the results from the simulations was lower than the measurements except for entry *J* in the reverberation chamber. The participants had the choice to only use half of the source-receiver positions due to computation time, only done by entry *K*. These variances in the calibration stage exceeded expected differences resulting from T_{30} calculations from RIRs, which were on the order of 3 % to 5 % [22], and would be expected to be even less for noise-free RIRs. The source of these discrepancies remains to be investigated.

3.2 Measured coupled system

A comparison between the physical scale model and the idealized statistical model is provided. Table 1 shows the coupled volume acoustic parameters acquired via scale model measurements and those using the statistical energy balance model. As the statistical model assumes homogeneous material distribution and does not take into account positions of the source or receivers [9], some differences are to be expected.

The decay rates DT_1 and DT_2 are in well agreement with relative differences of 8 % and 7 %, respectively. The most notable difference between the statistical model and the physical model concerns the bending point. The statistical model predicts a transition occurring later and lower in level than was measured with ΔBP_t=0.2 s and ΔBP_L=7 dB, taking into account the margin of the standard deviation.

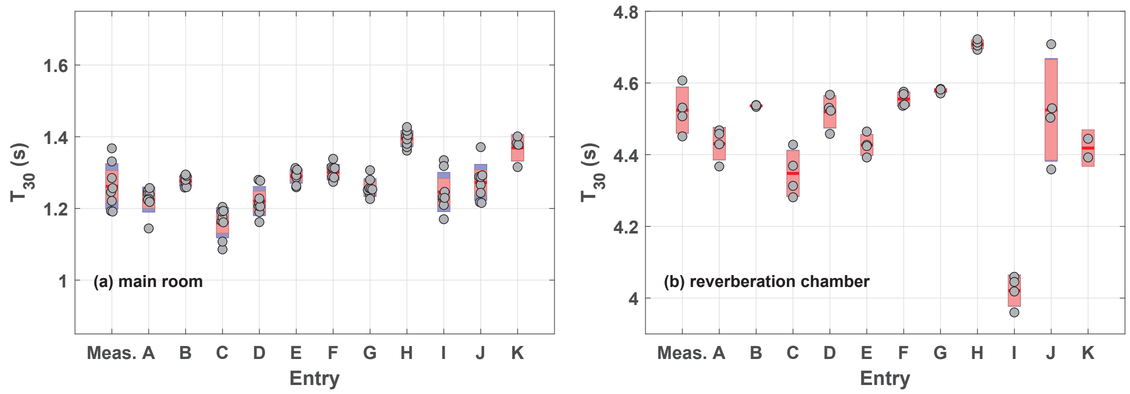

Figure 2. Reverberation times T_{30} from measured and simulated impulse responses for the two room in the uncoupled configuration: (a) main room and (b) reverberation chamber. Individual **S-R** pair data points are shown, including 95 % confidence intervals (red) and 1 Standard deviation (blue).

Table 1. Acoustical parameters for measurements in the scale model and the calibrated analytical model. Average values across the 8 source-receiver pairs with standard deviation.

Parameters	DT_1 (s)	DT_2 (s)	BP_t (s)	BP_L (dB)
Scale model	1.39 ± 0.16	3.46 ± 0.09	0.48 ± 0.04	-22.6 ± 1.3
Statistical model	1.29	3.71	0.73	-30.8

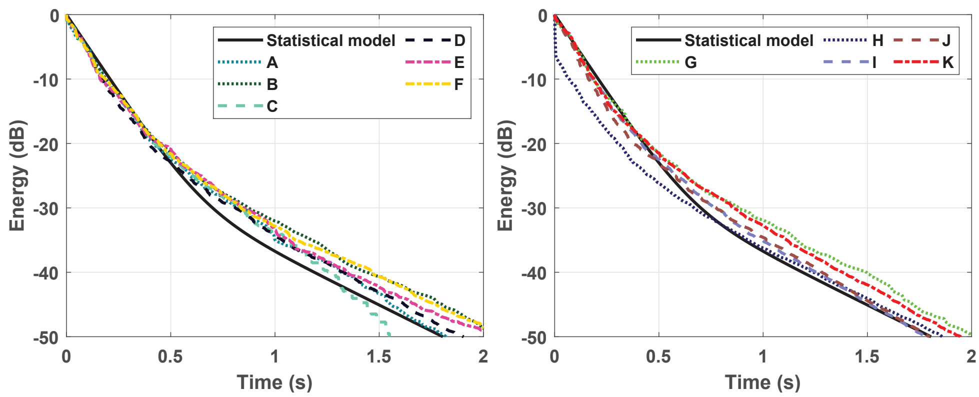

Figure 3. Statistical and simulated energy decay curves of the coupled configuration for the 1 kHz-octave band for **S1-R3** position. Results are split across 2 figures to improve readability.

3.3 Simulated coupled system

An example of the energy decay curves obtained from the measured and simulated room impulse responses for one source-receiver pair in the octave band of interest is presented in Fig. 3. The double-slope decay behavior expected for a coupled volume system is clearly visible for all entries and, based on visual impression, they seem to be in general agreement with the statistical model's EDC.

The results for all source-receiver pairs in the coupled volume configuration are summarized in Fig. 4. The remarks made earlier in the comparison between the physical model and the statistical model still apply in this case. Of primary interest are the decay rates of the different simulations, which approach those of the statistical model. For the main volume, DT_1 of entries A, C, D, I, J, K show good agreement with the statistical model, while the remaining entries over estimated it. The scale results are slightly higher than the statistical model, but not to the same degree. In almost perfect contrast, those performing well for DT_1 significantly underestimated DT_2, while the remaining entries, except H, provided comparable values to the statistical model.

Regarding the bending point, those methods correctly modelling DT_2 also matched the statistical model of BP_t, while the remaining entries result tend more towards the results of the scale model. Regarding BP_L, all methods overestimated with respect to the statistical model, with the same group A, C, D, I, J, K resembling more the results of the scale model.

The differences present for the uncoupled calibration phase are found in the coupled decay times as a general trend, but it is noted that entries with the highest calibration differences did not have the most extreme parameter predictions, *e.g.* entry I. In addition, entry H appears to have a significantly stronger direct sound component (see Fig. 3) which accounts for it being a relative outlier for BP_L.

Regarding trends across similar methods, while maintaining anonymity, it can be said that **Wave-based** methods were relatively consistent with respect to double-slope parameter results. The commonalities of the remaining methods makes it difficult to separate them further in any attempt to explain the observed data groupings.

Variances for parameter DT_1 are smaller than observed for the measured data, except for entry J. For other parameters, numerical simulations exhibit larger variances, except entries H and I; entries B and D have similar variances compared to measurements. All entries simulated the 8 source-receiver pairs, except K that only used source **S1**. Considering the same positions, this entry has a higher variance only for DT_2.

4 CONCLUSION

This study presented a simplified test case to compare the ability of various numerical methods for room acoustic simulations to reproduce or predict classical coupled volume behavior. Contrary to a previous study in

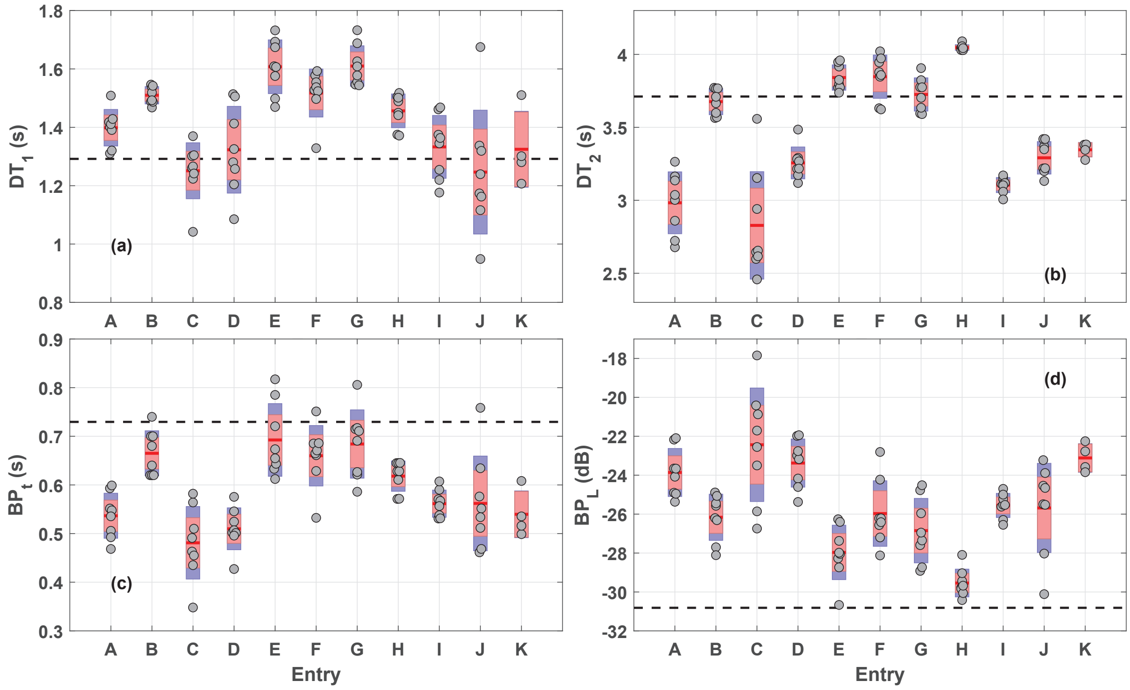

Figure 4. Comparison of resulting acoustical parameters from simulated RIRs. Individual **S-R** pairs are shown, including 95 % confidence intervals (in red) and 1 Standard deviation (in blue). Black dashed lines represent predicted values from the statistical model.

2013 [8], these results show that the tested methods are capable of representing coupled volume behavior, although not all results are consistent with statistical theory or comparable to measurements. Comparisons of methods shows the range of values (variance) across the 8 source-receive pairs varies significantly, potentially highlighting issues regarding local variations being poorly represented for some methods.

Perceptual thresholds regarding double-slope decay parameters have been examined [23]. For a system of coupled volumes with a configuration comparable to the one used in the present work, just noticeable differences were around 10 % for DT_1 and 20 % for DT_2, BP_t, and BP_L. Overall, differences observed among simulations exceeded these thresholds for at least one parameter compared with the statistical or the physical model.

We are now examining the feasibility of the next phase of this study, providing a more detailed geometrical model with specific material properties determined though laboratory measurements. Such input data should allow for direct comparisons of simulated results to the physical scale model, which is not appropriate in the current study due to the simplifications in the model and homogeneous application of material properties.

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