Numerical Coupling of Structural Response and Ground Motion in Multi-scale 3D Physics Based Simulations

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Abstract: Multi-scale 3D physics-based simulations are now widely used to generate free-field ground motions. Due to the high computational demand, these simulations usually do not account for local-site effects caused by the presence of the buildings. However, as a result of site-city interactions (SCI) existing structures can have an influence on wave propagation. A new module in the high-performance spectral element code SPEED (http://speed.mox.polimi.it/) is being developed to couple ground motions with the structural response. The buildings are approximated as nonlinear single/multi degrees of freedom systems (SDOF/MDOF) without requiring additional computational recourses. The main aim of implementing this module is to provide a more precise estimation of ground motion from the physics-based simulations at the city scale considering the source, path and local site effects. In this study, to prove the reliability of the proposed approach, we validate the structural response from numerical simulation with the recordings from the CAMUS III large scale experiment. The chosen benchmark building is modelled as a non-linear SDOF system with rigid footing resting on a sandy layer. The experimental structural responses are effectively reproduced with the simulations, even under different levels of ground shaking. These preliminary results show the effectiveness of the numerical coupling which is implemented in the proposed module.

Keywords: site-city interactions, 3D physics-based simulations

1. Introduction

The application of multi-scale 3D physics-based simulations (PBS) has become prominent in earthquake simulations, because of the realistic and site-specific characteristics of the simulated ground motions (Graves *et al.*, 2011; Schiappapietra and Smerzini, 2021; Stupazzini *et al.*, 2021). In addition, evolving knowledge about regional geology and the earthquake source has reduced the uncertainties in the estimation of the ground motion. Therefore, the use of PBS in regional seismic damage scenarios is becoming a standard.

Most of the PBS assume that the ground surface is free of traction and generate 'free-field' ground motions. In the presence of dense urban spaces, the dynamic structural response will lead to large inertial forces acting on the soil. Also, the impedance contrast between soil and foundation will act as a diffraction source. So, the simulated ground motions will be affected. These local-site effects are referred to as site-city interactions (SCI), and the magnitude of these effects depends on factors like the configuration of buildings, local geology, structural properties, soil properties etc. (Bard *et al.*, 2006). For example, the well-reported SCI effects during the 1985 Mexican earthquakes are because of soft sediments under Mexico city (Wirgin and Bard, 1996; Gueguen, 2000).

Several studies used numerical and experimental approaches to quantify the SCI effects, at a small scale (Kham *et al.*, 2006; Semblat, Kham and Bard, 2008; Schwan *et al.*, 2016). However, modelling the small features like budlings, soil sediments in a city-scale earthquake simulation is multiresolution in nature and computationally challenging. For this reason, not a lot of attempts were made to perform coupled simulations at city-scale. The domain reduction method (DRM) has proved to be effective in reducing computational cost, in this technique simulation is performed in several stages (Taborda and Bielak, 2011). Using the domain reduction technique, ground motions during the Northridge earthquake are coupled with the response of buildings present in the San Fernando Valley (Isbiliroglu, Taborda and Bielak, 2015), also PBS with a target frequency of around 11 Hz is performed for the Istanbul region (Zhang *et al.*, 2021).

In this work, we present a novel numerical approach to couple the structural response with ground motions in PBS, without the significant additional computational resources that are needed for PBS. The coupling is done with help of a new module (SPEED-SCI) in the high-performance code SPEED (Mazzieri *et al.*, 2013; Paolucci, Mazzieri and Smerzini, 2015; Infantino *et al.*, 2020), which is based on spectral elements using discontinuous galerkin (DG). The DG approach allows the use of non-conforming meshes. The buildings are idealised as single/multiple degree of freedom systems (SDOF/MDOF) with nonlinear shear force – deformation relationships. Then the base reaction forces of buildings are calculated at each time iteration and assigned as external point forces on top of the geophysical model. The user-defined constitutive models for SDOF/MDOF systems can further be integrated into the module with ease.

SPEED code has been used in the past to investigate SCI effects at different scales. In the PBS of the 2011 Christchurch earthquake, buildings were modelled as elastic blocks (Guidotti *et al.*, 2011). Lu *et al.*, (2018) modelled buildings as MDOF systems to replicate the SCI effects that were seen in the shake table experiment (Schwan *et al.*, 2016). Kato and Wang, (2022) modelled the congested buildings near a metro station in Hong Kong to explore their effect on the ground motion under plane wave excitation. In this work, we attempt to validate, if the simple structural models that are available in SPEED-SCI will be able to capture the nonlinear structural response of real-life buildings. So that, we can confidently extend this approach to explore city seismic response which also accounts for SCI effects.

In a series of large-scale experiments CAMUS I to IV, Combescure *et al.*, (2001) have designed the scaled specimens of a 5-story building with different reinforcement in RC walls. These experiments were also used as benchmarks to test the numerical tools. We have modelled the CAMUS III specimen as a non-linear SDOF system along with rigid concrete footing with the same dimensions as in experiments, overlying on top of the sand layer. Three different simulations were performed by changing levels of input plane wave motions, to validate both linear and nonlinear structural responses.

2. Numerical Method

Regional seismic damage scenarios provide important insights for efficient urban planning and earthquake preparedness. Due to the computational demand of multi-scale PBS, the ground motions generated for such scenarios are decoupled from the structural response. Addressing this issue, a new module (SPEED-SCI) has been introduced to the high performance, spectral element code SPEED (Mazzieri *et al.*, 2013), to integrate non-linear structural response and ground motions in PBS at an urban scale. SPEED is a versatile code that can handle complex earthquake sources, 3D heterogeneity of crustal media, non-linear soil behaviour, and has been used in several multi-scale simulations (Smerzini *et al.*, 2017; Sangaraju *et al.*, 2021). This new feature expands the capabilities of SPEED to generate ground motions considering wave propagation from the 'fault rupture to structure' framework, as shown in Fig. 1.

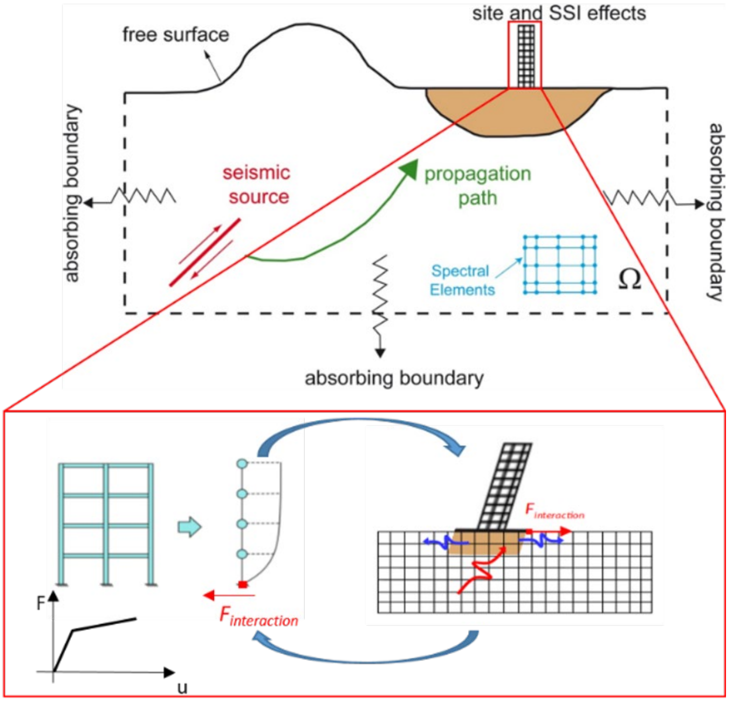

Fig. 1 - Wave propagation from seismic source to structure. The focused portion shows the modelling of the structures as multiple degree of freedom (MDOF) systems and the exchange of interaction forces between the structure and the elasto-dynamic domain.

In SPEED-SCI, buildings can be modelled using (i) single degree of freedom (SDOF) system with a fixed base or a flexible base, (ii) Multiple degree of freedom structures (MDOF) with a non-linear shear deformation model. Non-linearity can be introduced in structural response with help of bi-linear and tri-linear constitutive models. This approximation is numerically inexpensive, and the user can avoid the large number of input structural parameters, which may be cumbersome to obtain for the database of budlings at a city scale.

Now, we have two inter-dependent dynamic systems, (i) continuum that can be solved using the elasto-dynamic equation, to simulate ground acceleration ($\ddot{u}_{soil}$), (ii) dynamic vibration problem of SDOF/MDOF systems to calculate the base reaction forces (F_{int}). At any given time iteration (n+1) of PBS, SPEED-SCI exchanges forces between these two systems as presented in Fig. 2. The intermediate steps are explained below:

(i) The displacement of soil (${u_{soil}}^{n+1}$) at the n+1th iteration is calculated from elasto-dynamic equation, under the influence of seismic source and the base reaction forces calculated during previous iteration (${F_{int}}^{n}$).

(ii) Considering Δt as the time discretisation used in PBS, acceleration of soil ($\ddot{u}_{soil}^{n}$) at time $t^n = n\Delta t$, can be computed using central difference scheme (Eq. 1).

$$\ddot{u}_{soil}{}^{n} = \frac{{u_{soil}}^{n+1} - 2{u_{soil}}^{n} + {u_{soil}}^{n-1}}{\Delta t^2} \qquad (1)$$

(iii) The soil acceleration ($\ddot{u}_{soil}^{n}$) corresponding to the position of the structure is applied as an inertial force to SDOF/MDOF system. The dynamic equilibrium equation at time t^n, for structure, can now be written in the algebraic form (Eq.2), to find structural displacement (${u_{rel}}^{n+1}$) at time $t^{n+1} = (n+1)\Delta t$. In the Eq. 2, m and c are mass and damping matrices respectively, F_{int}^{n} is the force developed in structure at t^n, which is a function of structural displacement ${u_{rel}}^{n}$ depending on constitutive law.

$$m\frac{{u_{rel}}^{n+1} - 2{u_{rel}}^{n} + {u_{rel}}^{n-1}}{\Delta t^2} + c\frac{{u_{rel}}^{n+1} - {u_{rel}}^{n-1}}{2 * \Delta t} + F_{int}^{n}({u_{rel}}^{n}) = -m{\ddot{u}_{soil}}^{n} \qquad (2)$$

(iv) Obtaining base reaction force of structure ${F_{int}}^{n+1}$ at time t^{n+1}, and applying it back on soil in the next iteration.

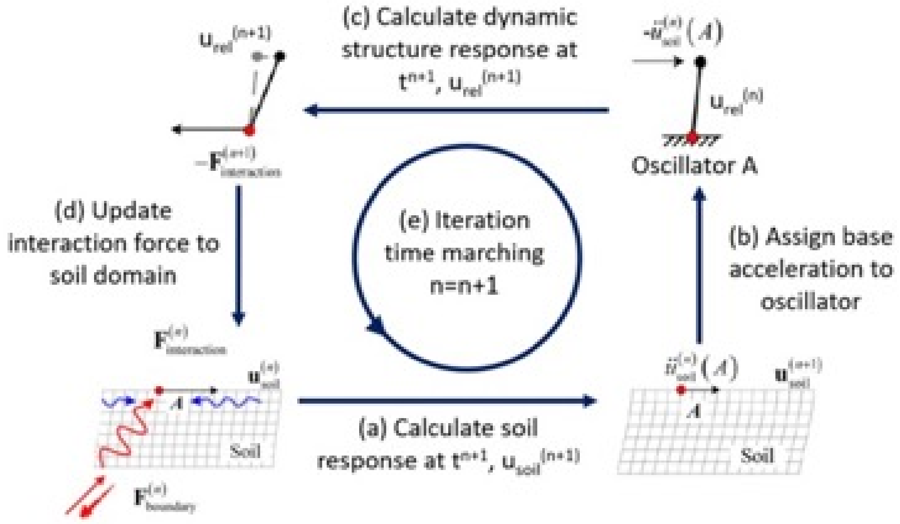

Fig. 2 - Coupling of ground motion and structural response at time iteration tn+1.

3. Validation with shake table experiments – CAMUS III specimen

3.1. Numerical setup and calibration of structural parameters

In the series of dynamic laboratory shake table experiments, four specimens CAMUS I to IV, are modelled and subjected to different levels of seismic excitation (Combescure *et al.*, 2001). These specimens are 1/3 scaled models of 5 story structure with 2 RC walls. CAMUS I to III specimens have different steel reinforcement ratios and are anchored to the shaking table to replicate the fixed base. CAMUS IV is similar to the CAMUS I specimen, except the foundations, are supported on top of the sand layer above the shaking table, to explore soil-structure interaction. This paper focuses on the CAMUS III specimen and validates the structural response calculated from SPEED-SCI with experimental data.

The numerical domain to simulate CAMUS III tests is shown in Fig. 3. The model consists of a sand layer at the bottom and a rigid concrete block is placed on top of the sand. The material properties used are presented in Table 1. The dimensions of the rigid block are 2.m by 1.7m, similar to that of the floor dimensions of the specimen. The motion of the shake table is applied as plane wave excitation along x-direction on the bottom surface of the domain at a normal incidence. Lateral surfaces of the sand layer are constrained in y and z directions, while the absorbing boundary condition is assigned to the bottom surface. The size of the spectral element in the mesh is around 1.2m with a spectral degree of 4, this will allow the simulation of wave propagation accurately up to 30Hz frequency.

Figini *et al.*, (2012) have modelled the CAMUS III specimen as a cantilever beam, after considering just one RC wall, and were successful in reproducing the structural response. It is also pointed out that the experimental stiffness of the RC wall is nearly 0.7 times the numerically estimated value. Following these two assumptions, the specimen is modelled as an SDOF system with a concentrated mass (m_s) of 12527 kg and a damping ratio of 2%, even though the actual mass is around 36000kg.

Table 1 Properties of materials in the simulation domain

Block.	Density (kg)	Shear Wave velocity (m/s)	Pressure wave velocity (m/s)	Thickness (m)
Bottom (Magenta)	1671	200	350	1.2
Middle (Green)	1671	200	350	3.6
Top (Yellow)	2350	2300	4100	0.6

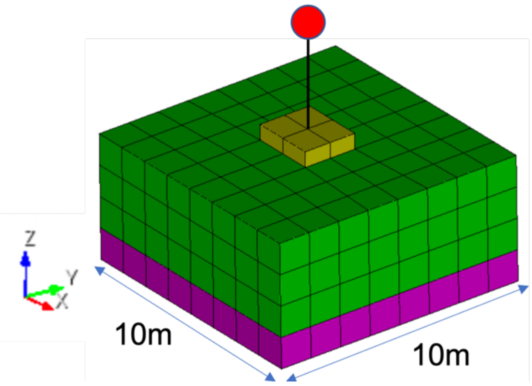

Fig. 3 - Numerical Domain

During the experiments, the specimen is subjected to 12 different ground motions with increasing levels of excitation. The peak ground acceleration (PGA) of these motions is between 0.05g to 1.35g. Here we considered the experimental tests corresponding to 3 signals covering a range of PGA values. The signals are hereafter termed as (A) Nice 0.09g (B) Nice 0.64g (C) Melendy Ranch 1.35g. According to the measurements before the loading, the fundamental frequency of the specimen structure is estimated to be around 6.8 Hz. However, repeated loading of the structure has resulted in crack openings and damage, thus reducing the stiffness. The fundamental frequency of structure was reduced to 3.8Hz, towards the end of the experiments.

3.2. Validation of structural response

In order to capture both linear and non-linear responses of the specimen subjected to excitation of signals A, B and C, different simulations are performed assuming (1) Linear and (2) Bi-linear force-deformation relationships in structural response. The linear model is based on the specimen behaviour in the initial stage of the experiment, where it is subjected to low-level excitation. The nonlinear model is based on structural behaviour when it is subject to high-level excitations, so a reduced stiffness is assumed even in the elastic portion of non-linear structural behaviour. The structural parameters of the SDOF system under these two approximations are shown in Table 2.

The initial simulations were performed using the linear SDOF system with low-level excitation of signal A (Case A1). The acceleration response of the structure at the fourth-floor level from the experiment (blue line) is compared with the response of the SDOF system (red line) (Fig. 4a). The response at the fourth-floor level is considered for comparison instead of the top floor since the effective height of the SDOF system will be lower than the actual structure. The structural acceleration is reproduced precisely both in the time and frequency domain from the simulations, even though the structure is modelled using a simple SDOF system. As expected, simulated SDOF response at higher frequencies (greater than 10Hz) is the same as the input motion, but slightly different from the experimental record owing to presence of noise. This reinforces the confidence that we can resolve higher frequencies effectively in simulations without any artefacts from boundary conditions.

Further, the same linear SDOF model with a fundamental frequency of 6.1Hz is used to simulate response due to higher-level excitation of signal B (Case B1). The simulated and recorded structural acceleration are similar in the time-window 2.2 – 3.0 sec (Fig. 4b). However, after this window, it can be seen that, the time period of pulses in recorded response is significantly longer compared to linear SDOF response. The stiffness of the specimen was reduced because of non-linearity and the frequency content from the experimental record is significantly different compared to the linear response. For this reason, only the Bi-linear constitutive model is used for the SDOF system in simulations with high-level excitations. The yield shear force in the bi-linear model is calibrated based on the hysteresis behaviour of the specimen that has been observed in experiments.

Table 2 Structural Parameters of SDOF system

	Mass (kg)	Fundamental Frequency	Yield Strength (kN)	Post yield stiffness ratio
Linear	12527	6.1 Hz	-	-
Bi-Linear	12527	3.9 Hz	70	0.2

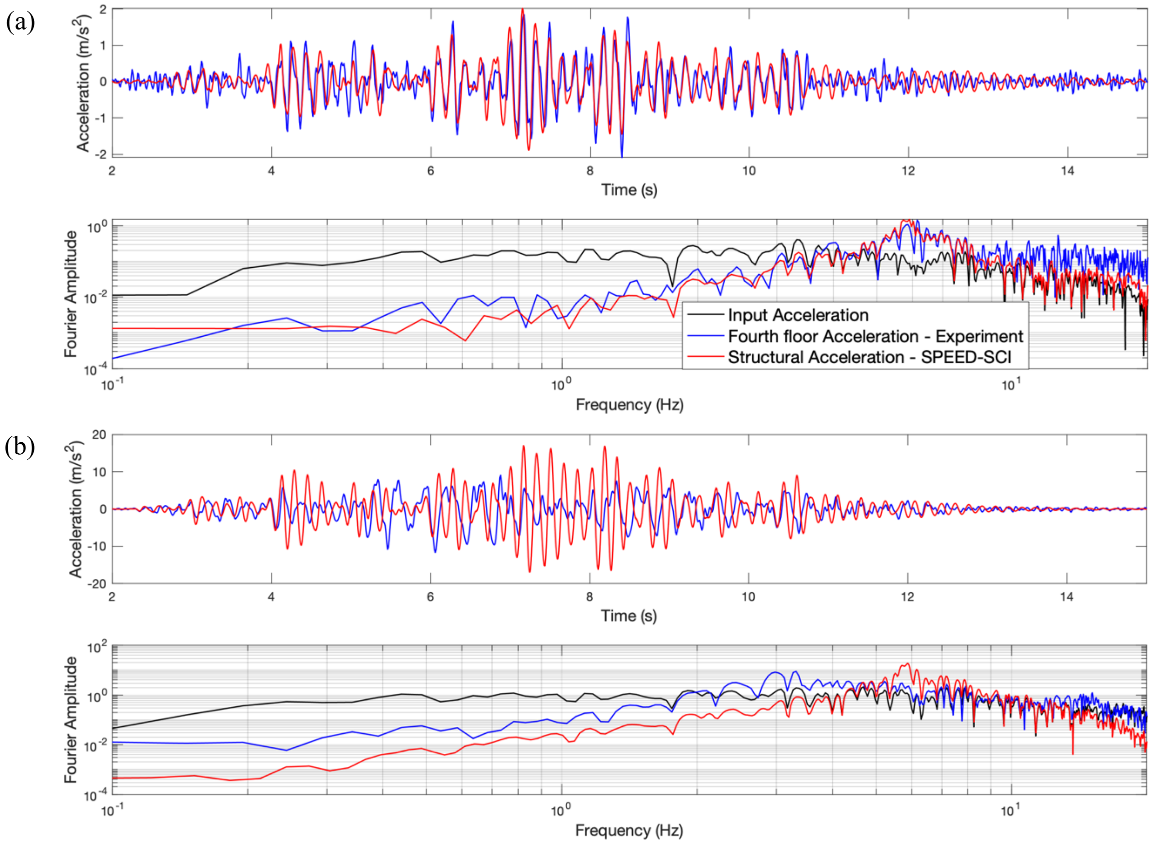

Fig. 4 – Comparison of Acceleration time history and fourier spectra using linear SDOF system, (a) Case A1 - Nice 0.09g (b) Case B1 - Nice 0.64g . The input acceleration at shake table is shown in black line. The structural acceleration from experiments, that has been recorded at fourth floor level is shown in blue line. The structural acceleration of SDOF system from simulations is shown in red line.

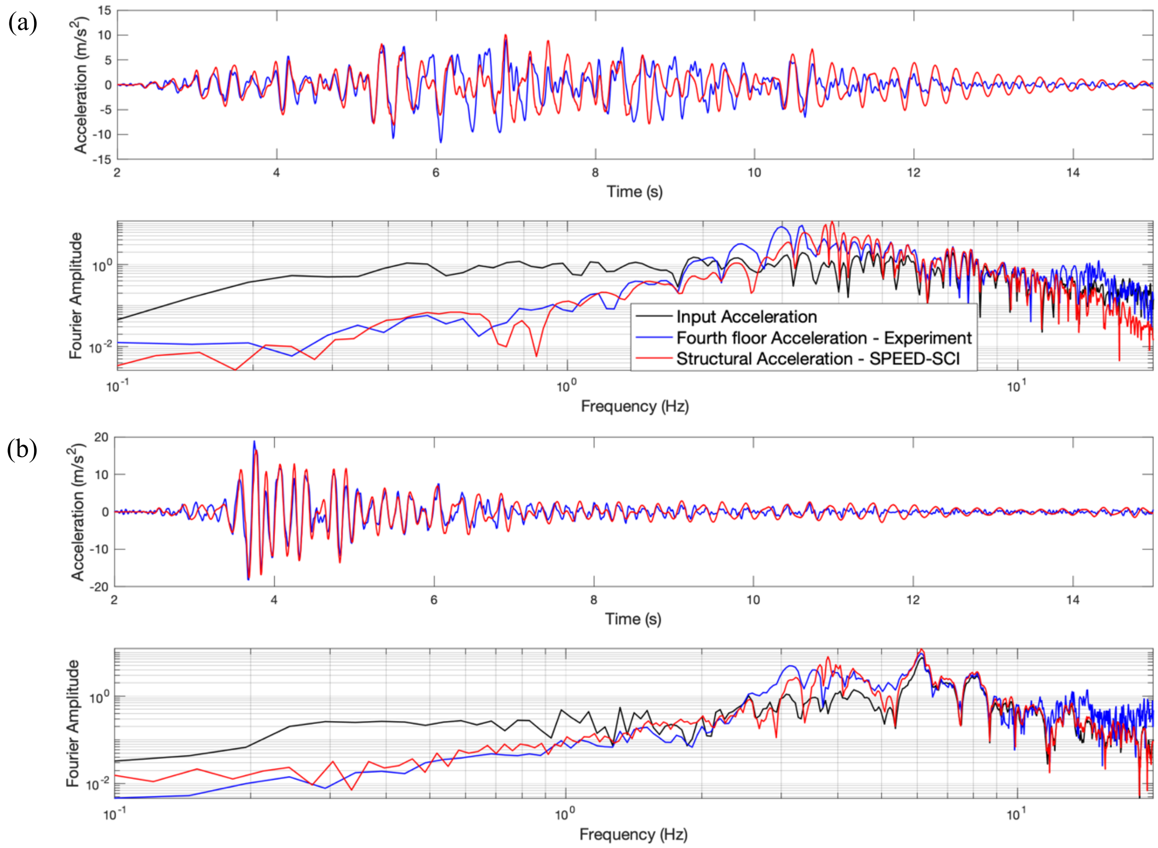

Fig. 5 - Comparison of Acceleration time history and fourier spectra using Bi-linear SDOF system (a) Case B2 - Nice 0.64g (b) Case C2 – Melendy Ranch 1.35g. The input acceleration at shake table is shown in black line. The structural acceleration from experiments, that has been recorded at fourth floor level is shown in blue line. The structural acceleration of SDOF system from simulations is shown in red line.

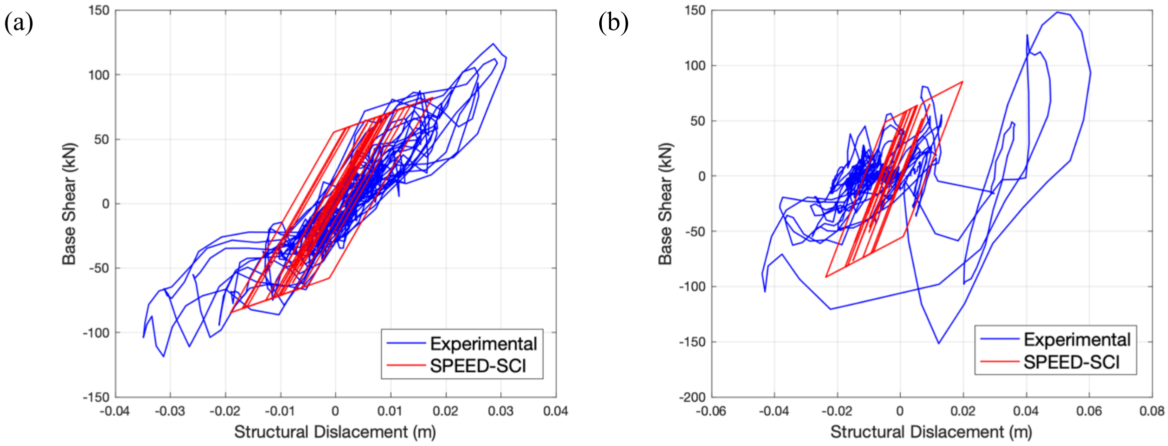

Fig. 6 – Comparison of Force-displacement behaviour of simulations with experimental data. (a) Case B2 - Nice 0.64g (b) Case C2 – Melendy Ranch 1.35g. The structural response from experiments are shown in blue. The structural response of SDOF system from simulations is shown in red.

Fig. 5 shows, the comparison of structural acceleration when bi-linear SDOF is subjected to signal B (Case B2), and signal C (case C2). The simulated response under both high-intensity excitations is now closer to the recorded time history. Also, the frequencies corresponding to peaks in the fourier amplitude are also similar. Fig. 6 shows the hysteresis behaviour of the SDOF system in Case B2 and Case C2, the hysteresis behaviour simulated using the simple bi-linear model is analogous to the experimental data. There are some discrepancies in hysteresis especially when displacements are large, one may need more sophisticated consecutive behaviour to capture the actual behaviour of specimen.

4. Conclusions

The presence of structures in densely packed urban environments can influence ground motions in addition to local-site effects. Modelling the ground motions coupled with structural response is computationally expensive and are generally ignored. A new module (SPEED-SCI) is being implemented in high-performance spectral element code SPEED to couple the structural response within the 3D physics-based simulations.

The SPEED-SCI module is computationally inexpensive as structures are modelled as Single or Multi Degree freedom structures (SDOF/MDOF). This module is used to simulate the structural response of the CAMUS-III specimen under different levels of excitation. Even though the structure is modelled using the SDOF system, both linear and non-linear responses of specimen are reproduced.

This work focus on validating the coupling algorithm used in the SPEED-SCI module and modelling the response of just one building. However, the main objective is to use this tool to perform state-of-art 3D simulations at a city-scale, considering wave propagation from fault rupture to structure and exploring the impact of site-city interactions on ground motion.

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