Comparison of conventional modelling techniques with observations from the UC Physics Building in the Canterbury earthquakes

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2013
NZSEE
Conference

ABSTRACT: This paper examines the predictive capability of conventional modelling techniques with the observed response of the University of Canterbury (UC) Physics Building in the Canterbury earthquakes. The Physics Building is an eight storey reinforced concrete building which has 10 multidirectional accelerometers located on four different floors. A set of ten earthquake events are considered, including the 4 September 2010 and 22 February 2011 earthquakes. In the longitudinal axis of the building, a 1D ‘stick’ model was capable of accurately predicting the peak roof displacement. However a 1D model was not able to accurately predict the correct maximum deflected shape, for which a 2D model was required. Both 1D and 2D models notably under predict deflections in the transverse axis of the building because of significant flexibility from soil-structure interaction in this direction. A rotational spring added to the base of the 1D transverse axis model subsequently results in an adequate prediction of the deflected shape and peak roof displacement. This study therefore illustrates the importance of considering SSI effects, which can often be adequately addressed using simple modelling techniques and parameters estimated from existing literature.

1 INTRODUCTION

Instrumented buildings can be considered as full scale models, with the correct boundary and initial conditions, which are excited during earthquake events. Thus, they provide important system-level data on how actual structures behave during real earthquakes, which can be difficult if not impossible, to obtain using laboratory experiments on sub-systems or components in isolation. Such instrumental data is therefore invaluable for the validation of design techniques and numerical analysis models.

In 2006, the Physics section of the Rutherford Building at the University of Canterbury was instrumented with ten multidirectional accelerometers. These accelerometers recorded the earthquakes on 4 September 2010 and 22 February 2011, as well as the many subsequent aftershocks. The data recorded provides a unique opportunity to examine the behaviour of this structure under moderate and strong ground motions. To date, there have been two known studies using this data. Zhao and Uma (2011) directly examined the instrumental response during the September 2010 earthquake, while Butt and Omenzetter (2012) identified the fundamental periods, mode shapes and damping ratios of the structure for numerous earthquakes. In addition to the analysis of earthquake-induced vibrations, Johnstone (1970) and Reay (1970) also examined various aspects of the response of the structure using low-amplitude forced-vibration testing, including estimation of vibration modes, and in particular the significant rotation at the base of the structure due to soil-structure interaction.

As well as using instrumental records for structural identification, as exemplified by the aforementioned two studies, such records can also be used to examine the predictive capabilities of numerical models by comparing the observed and predicted responses. Such validation exercises are useful to examine the predictive capability of conventional methods that are utilized in routine structural analysis. Conventional analysis models can represent the structure in one, two or three dimensions and can have linear and/or nonlinear material components as well as different boundary conditions in attempting to reproduce the salient features of the actual response.

2 UC PHYSICS BUILDING AND INSTRUMENTATION

The Rutherford Building, located at the University of Canterbury, is an eight storey reinforced concrete building comprised of three sections, each separated by a seismic gap. The Physics Building makes up the North section of the entire building and is approximately 58m long (longitudinal direction) by 15m wide (transverse direction). In the transverse direction the structure consists of three shear walls and 20 gravity frames as shown in Figure 1. In the longitudinal direction the structure consists of two parallel systems with eleven 3m wide walls and ten deep beam elements at each floor. The inter storey height is 3.8m. The foundation is a padded foot system which follows the outline of the building and is 2.5m deep and 2.1m wide.

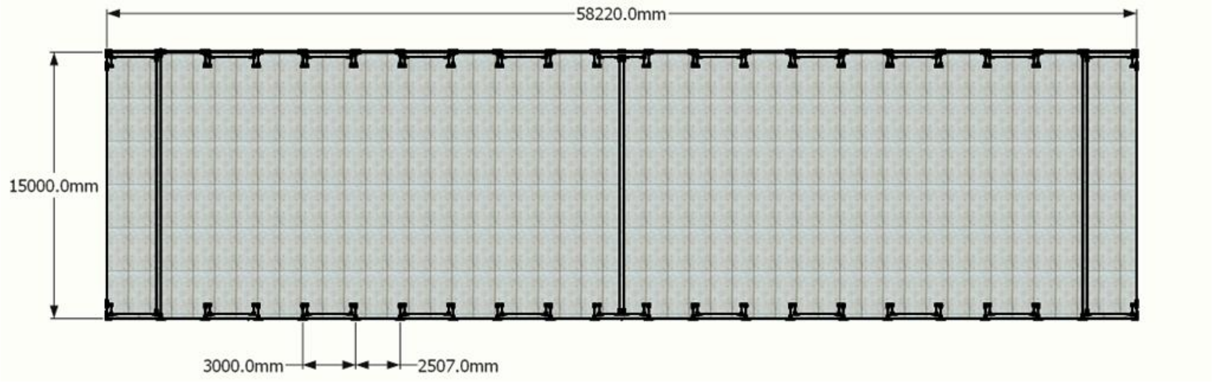


Figure 1. Plan view of the Physics Building.

Ten multidirectional triggered acceleromters were installed in the Physics Building in 2006. As shown in Figure 2, there are four on the first floor, two on the fourth floor, two on the sixth floor and two on the eighth floor. The accelerometers are fixed to the shear walls so they are not located exactly at the base of each floor. All of the raw acceleration records were processed using a 4th order Butterworth filter with corner frequencies of 0.2Hz and 25Hz. The four vertical sensors on the ground floor are used to determine rocking occuring at the base, while the three horizontal senors aligned at each end of the building are used to calculate the vertical distribution of response.

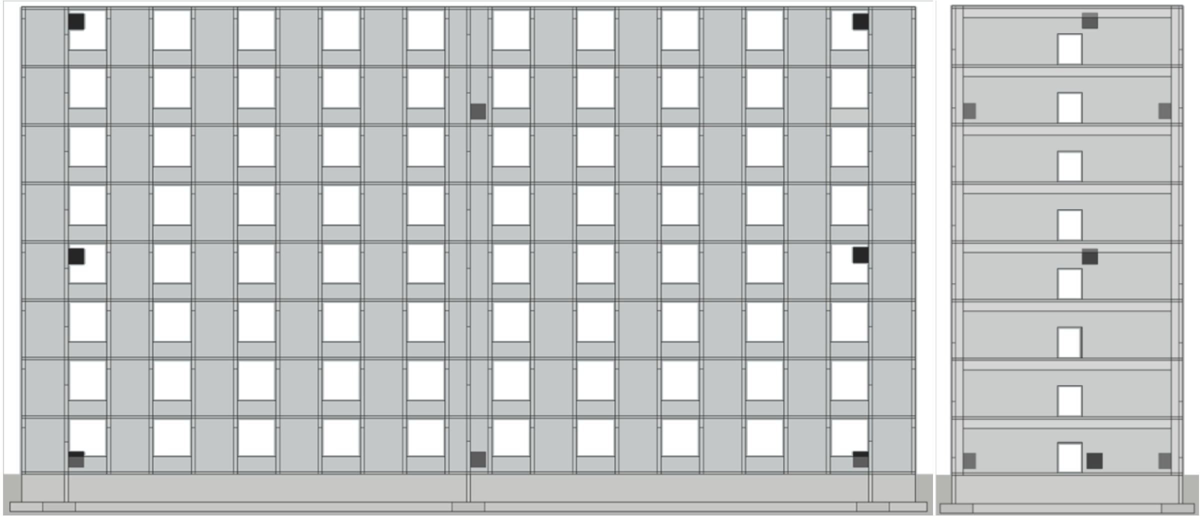
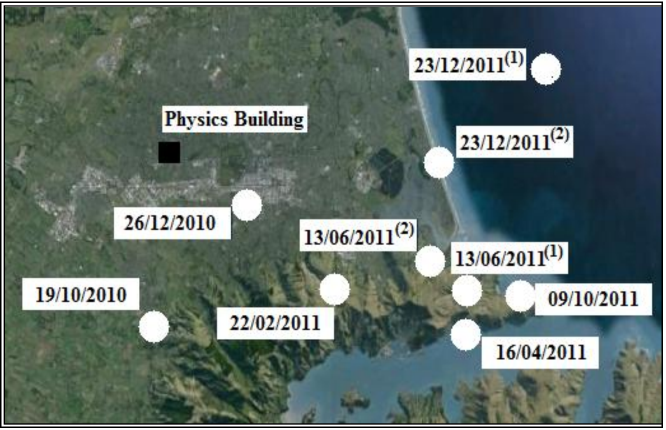


Figure 2. Longitudinal (left) and transverse (right) elevations of the Physics Building with instrument locations.

3 EARTHQUAKE EVENTS CONSIDERED

A range of earthquake events are considered in this analysis with varying magnitude and source to site distances. These events produced recorded ground motions with a range of amplitudes, enabling a range of structural responses to be examined, including any possible non-linear behaviour. The list of the earthquakes considered are shown in Table 1 along with their corresponding epicentral locations.

Table 1. Summary of earthquakes considered.

Earthquake	Magnitude	Location
04 September 2010 - 04:35*	7.2	
19 October 2010 - 11:32	4.8	
26 December 2010 - 10:30	4.7	
22 February 2011 - 13:50	6.2	
16 April 2011 - 17:49	5.0	
13 June 2011 - 13:01	5.3	
13 June 2011 - 14:20	6.0	
09 October 2011 - 20:34	4.9	
23 December 2011 - 13:58	5.8	
23 December 2011 - 15:18	5.9	

*The location for this earthquake is to the left of the map.

4 NUMERICAL MODELLING AND PREDICTION OF OBSERVATIONS

4.1 One dimensional fixed based model

A multi-degree of freedom 1D ‘stick’ model is one of the simplest ways in which a building can be modelled, where the total mass and stiffness of each floor is lumped into one node and element. The model has a fixed base and all elements are elastic. A critical parameter that affects the displacement of the model is the fundamental period which is proportional to the ratio of floor mass to stiffness.

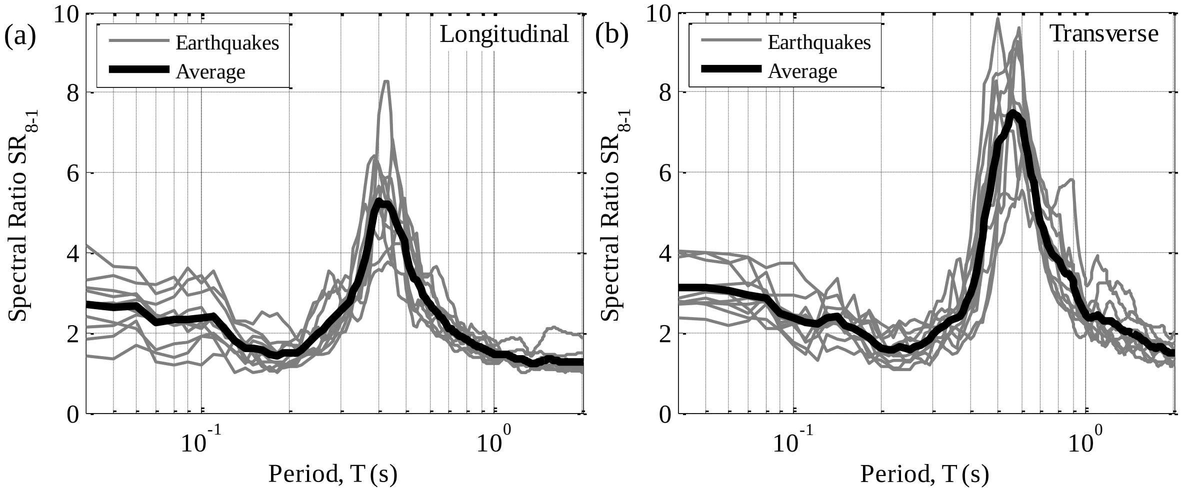


Figure 3. Response spectral ratios for the (a) longitudinal and (b) transverse directions.

The simplest way to find the fundamental period of the building is to perform a spectral ratio analysis. This involves dividing the pseudo-spectral acceleration (SA) from the eighth floor by the SA from the ground/first floor. The period at which there is a maximum ratio is considered to be the fundamental period. The spectral ratios in the longitudinal and transverse directions are shown in Figure 4 for all of the considered earthquakes as well as the average. It can be seen that the identified fundamental period in the longitudinal and transverse directions are 0.42s and 0.59s, respectively. With the fundamental period known from the instrumental records, and the mass estimated from structural drawings, the inter-storey stiffness of the 1D model can be obtained.

By applying the recorded ground motions at the base of the structure as input to the numerical model, the predicted displacements can be compared with the relative displacements observed on the fourth, sixth and eighth floors. These comparisons can be analysed on a case-by-case basis as shown in Figure 4 (a) in the longitudinal direction, and Figure 4 (c) in the transverse direction, for the 22 February 2011 earthquake. These figures also show the range of displacements predicted when the stiffness of the model is adjusted by ±20%.

The predictions vs. observations for all the earthquake events can be compared by normalising all values with respect to the predicted eighth floor deflection, as seen in Figures 4 (b) and (d). Figure 4 (b) shows that the 1D longitudinal model can accurately predict the maximum deflected shape for most earthquake events. For an individual earthquake event the variation between observation and prediction as depicted in Figure 4 (b) is in the range of 20%. As indicated by the large envelope in Figure 4 (a), when the stiffness is varied for the longitudinal direction model it results in a large difference in the displacement amplitudes (a roof displacement range of 44%), In contrast, a smaller sensitivity to stiffness variation is seen for the transverse direction displacement, as shown in Figure 4 (c) (a roof displacement range of 17%). This difference illustrates that the variability of the displacement amplitudes is a function of the vibration period, as a result of the characteristics of the ground motion.

It can also be seen in Figure 4 (c), that despite the variation in stiffness, the predicted roof displacement in the transverse direction is still under the observed maximum. This under prediction occurs for all earthquakes considered as illustrated in Figure 4 (d). Despite this, it can be seen that there is a general agreement between the predicted and observed fourth floor displacements. These results suggest that the displaced shape of the structure is incorrectly predicted as a result of either nonlinear behaviour or foundation flexibility due to soil-structure interaction. This underestimation is inferred due to soil-structure interaction as examination of Figure 3 does not show an increase in period for ground motion records of larger intensity, which would be indicative of a building that has experienced nonlinear behaviour.

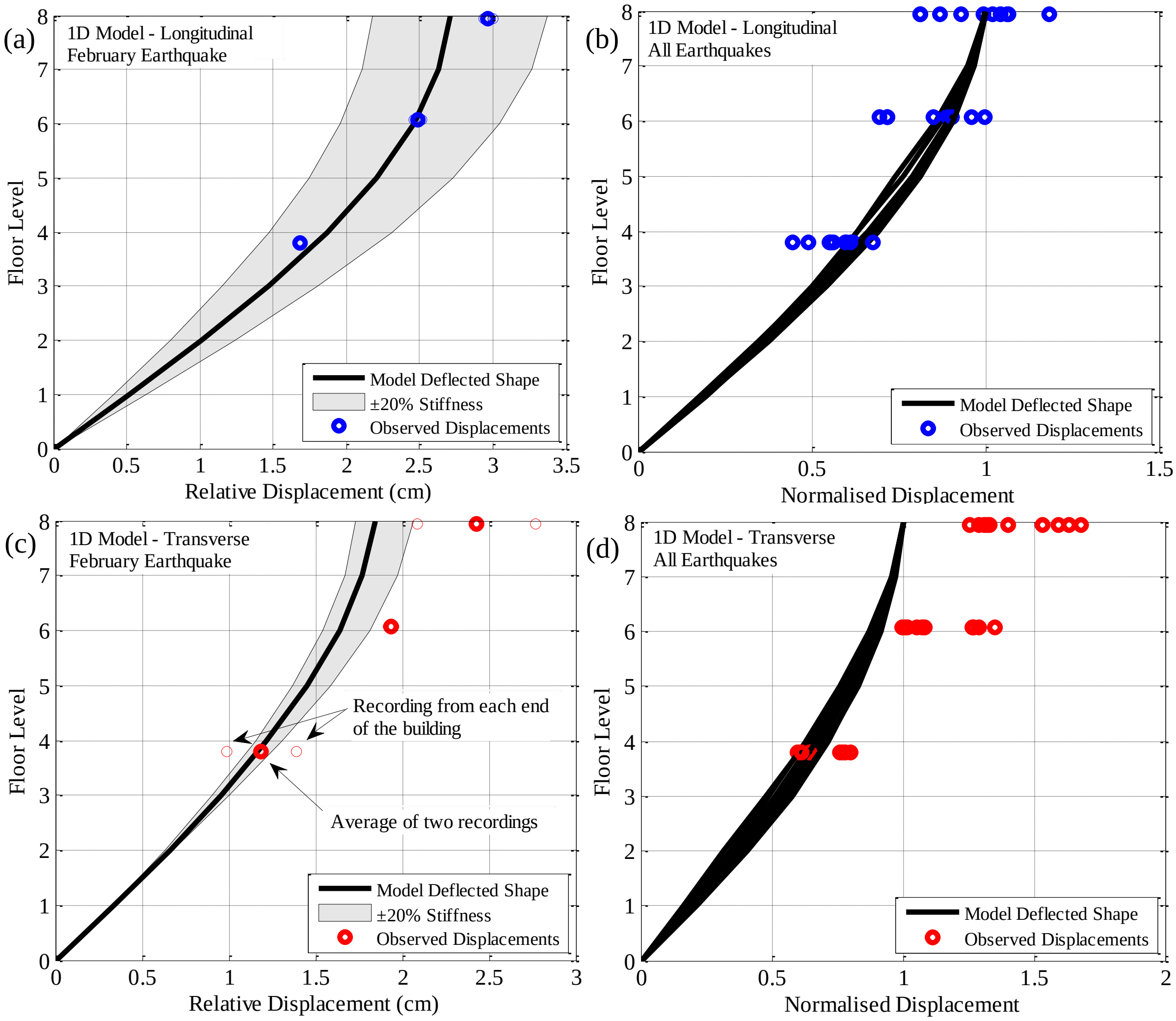


Figure 4. Predicted maximum deflected shape compared with observations for 1D model in the longitudinal direction for (a) February earthquake and (b) all earthquakes and for the transverse direction for (c) February earthquake and (d) all earthquakes.

4.2 Two dimensional fixed based model

A two dimensional (2D) model, which includes multiple vertical elements and horizontal elements, was developed following the analysis results of the 1D model. In the transverse direction the shear walls are divided into two walls connected with a deep beam as shown in Figure 2. In order to obtain the correct vibration periods of the structure in each direction (as inferred from spectral ratio analysis), the stiffness of the elements was reduced. Any moment resisting capacity of frames was not considered in the transverse direction model because they are considerably more flexible than the shear walls. The stiffness of the floors was also not included in this 2D analysis.

The predicted and observed displacements from the February 2011 earthquake are shown in Figure 5 (a) and (c) for the longitudinal and transverse directions, respectively, as well as the prediction variation resulting from a ±20% variation in stiffness. Again the longitudinal direction model provides a good match with the observed data. The predicted displacements from the 2D longitudinal model (Figure 5 (a)) also follow the observed shape better when compared with the 1D model prediction (Figure 4 (a)). In the transverse direction, the 2D model prediction provides smaller displacement amplitudes than the observed displacements for all cases, as was seen for the 1D model also (i.e. Figure 4(d)). This confirms that the use of 1D modelling was not the cause of the under-prediction of displacements in Figure 4. Similar to the results from the 1D analyses, when the stiffness of the elements in the models are varied, the amount of change of the predicted deflection is much larger in the longitudinal direction.

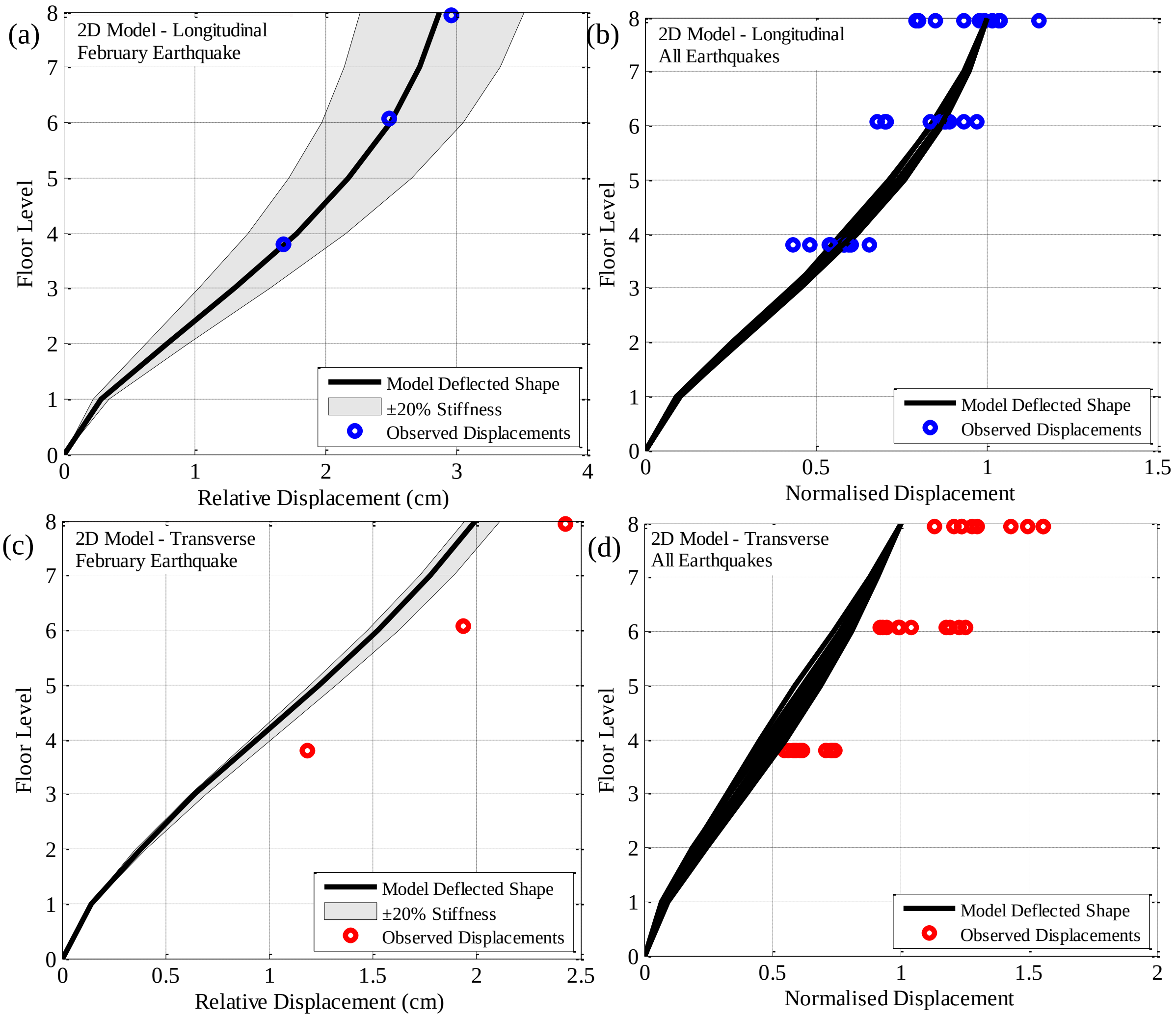


Figure 5. Predicted maximum deflected shape comapared with observations for 2D model in the longitudinal direction for (a) February earthquake and (b) all earthquakes and transverse in the direction for (c) February earthquake and (d) all earthquakes.

4.3 Consideration of soil-structure interaction in the one dimensional model

To account for underprediction of both 1D and 2D models in the transverse direction, a 1D model with foundation flexibility was created by considering a rotational spring at the base. This made the model more flexible however the element stiffness was not changed as the fundamental period only increased by 0.01s and 0.001s in the transverse and longitudinal directions, respectively. The rotational stiffness of the spring was determined using an empirical equation (Gazetas, 1991), which is based on the foundation depth, width and length as well as the soil shear stiffness. The soil stiffness was calculated based on correlations between CPT and shear wave velocity data (Robertson, 2012). Two CPT tests performed in the vicinity of the structure which found that the top 2.5m of soil had a shear wave velocity of 175m/s while below 2.5m, it was 230m/s. For the 1D SSI model, 40% of the elastic shear stiffness was used to allow for nonlinear soil behaviour resulting during finite soil strains.

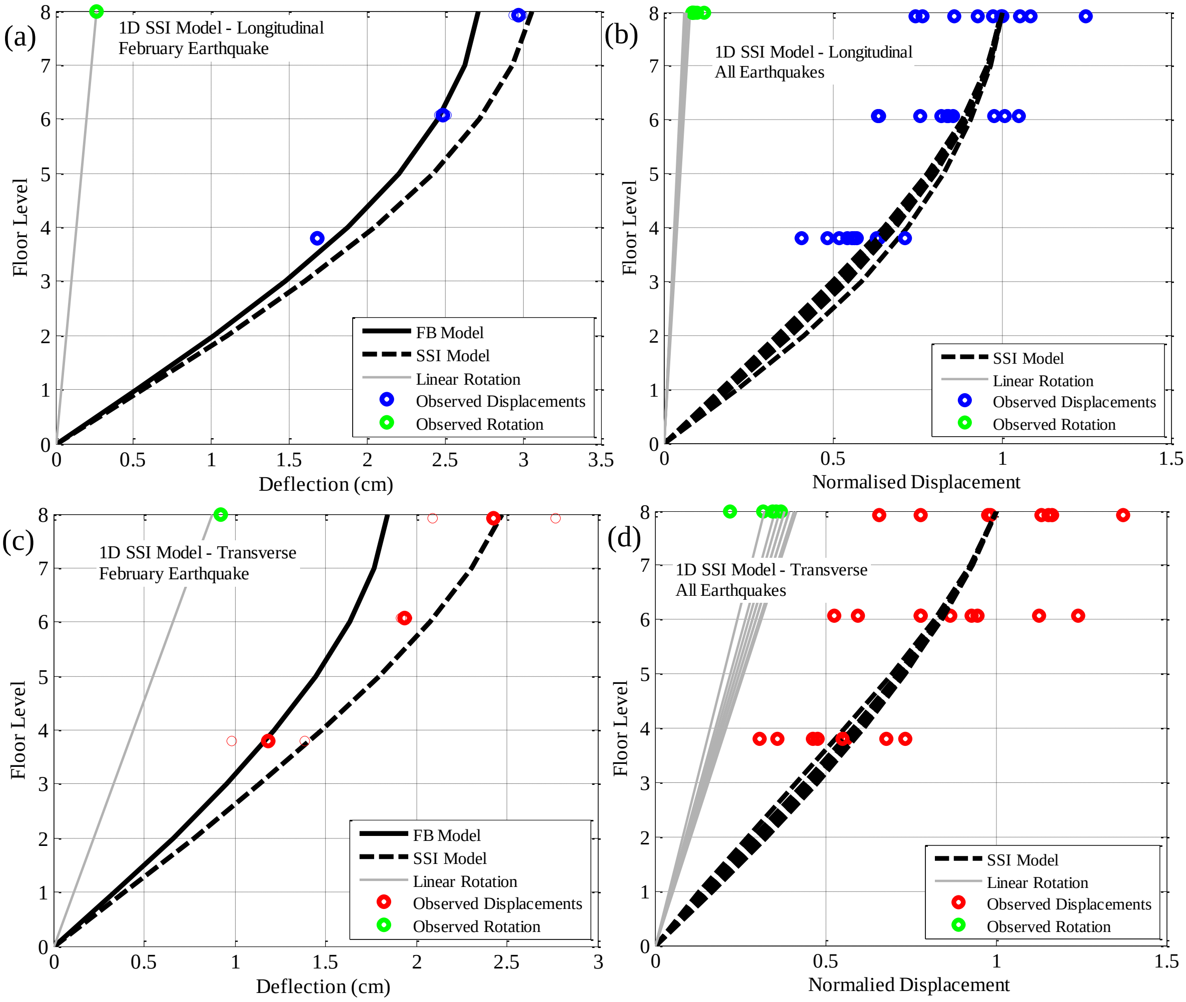


Figure 6. Predicted maximum deflected shape comapared with observations for 1D SSI model in the longitudinal direction for (a) February earthquake and (b) all earthquakes and in the transverse direction for (c) February earthquake and (d) all earthquakes.

This 1D-SSI model was used to predict the maximum displacement for all ten earthquakes with the results for the February earthquake, in particular, shown in Figures 6 (a) and (c); and normalised displacements for all events shown in Figures 6 (b) and (d) for the longitudinal and transverse directions, respectively. In Figures 6 (a) and (c) it can be seen that the rotational spring increases the predicted displacement, particularly in the transverse direction. As a result, there is subsequently a significantly better correlation between predicted and observed displacements in the transverse direction with the SSI model as compared to the fixed-base model. Figures 6 (b) and (d) also show the predicted and observed percentage contribution to the roof displacement from the rotation at the base. It can be seen that in both directions, the predicted and observed percentages are very similar for all earthquakes. This percentage contribution is equal to approximately 10% in the longitudinal direction and 30% in the transverse direction. A similar percentage was found by Reay (1970) during small-amplitude forced-vibration testing.

5 DISCUSSION

5.1 Comparison between normalised displacement shape of models

Figure 7 provides a comparison between the different models and observations by normalizing all results by the observed displacement on the eighth floor. It can be seen that across all the considered earthquake events, the observed normalised deflections are very similar suggesting that irrespective of how large the ground motion was, the building displaced in a similar way and only the amplitude of the displacement was different, indirectly illustrating that nonlinear effects are unlikely to have been pronounced. Figure 7 also illustrates the predicted displacement of the three models in the longitudinal direction are generally very similar, in relation to the large variation between the models in the transverse direction.

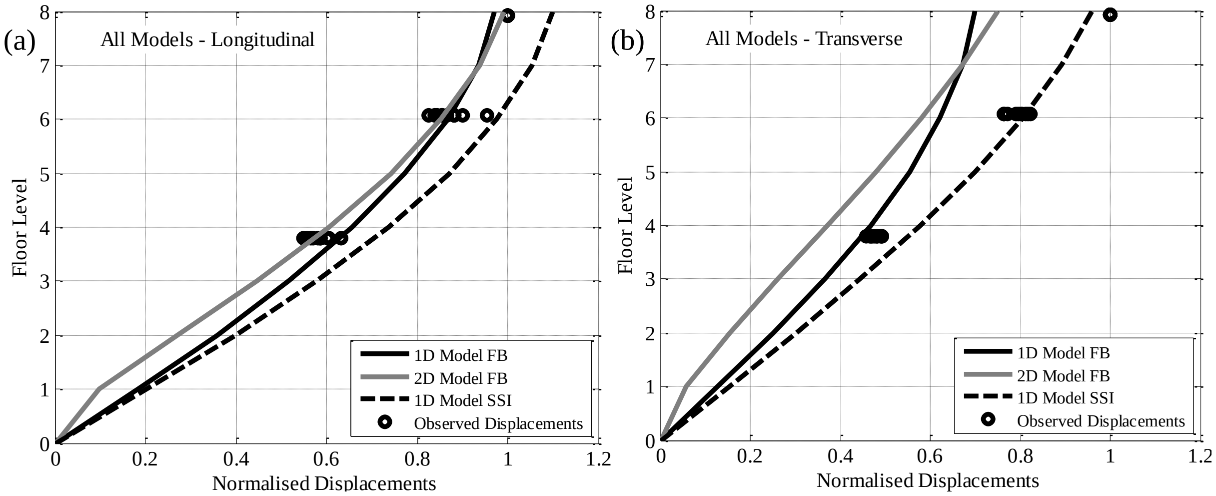


Figure 7. Comparison between all models predicted maximum deflected shape with normalised observations in the (a) longitudinal and (b) transverse direction.

5.2 Comparison of modelling accuracy

Table 2 provides the average relative errors between predictions and observations across all 10 earthquake events considered. A negative value implies that the model under predicts the observation. It can clearly be seen in Table 2 that, in the longitudinal direction, the 2D model is the most accurate over all floor levels, and the foundation flexibility adjustment to the 1D model causes an over prediction of displacement at all floor levels.

In the transverse direction the 1D-SSI model provides the best prediction. The significance of SSI in the transverse direction is likely the result of the large aspect ratio of the building height to width in this direction. Although the 1D SSI model provides the best displacement predictions out of these three models, it clearly does not predict the correct deflected shape. The shape predicted from the 2D model appears to be a better fit with the data if a linear rotation was added. As such, future research will examine the predictive capability of a 2D-SSI model.

Table 2. Average percentage error of the models compared with observations.

	Longitudinal			**Transverse**		
	1D FB	**2D FB**	**1D SSI**	**1D FB**	**2D FB**	**1D SSI**
8th Floor	-2.9%	-0.8%	9.9%	-30%	-25%	-4.1%
6th Floor	-0.3%	-1.7%	11%	-17%	-21%	1.1%
4th Floor	4.5%	-0.9%	12%	-3.1%	-13%	7.3%

6 CONCLUSIONS

In this paper the strong ground motions recorded in the instrumented Physics Building at the University of Canterbury were used to examine the predictive capabilities of conventional structural analysis modelling techniques. The fundamental period of the structure was found in both principal directions by a spectral ratio analysis. Initially, a multi-degree-of-freedom 1D ‘stick’ model was created to have the same period that had been observed. The 1D model provided a good prediction for the longitudinal direction, however it under predicted the displacement in the transverse direction by up to 30%. The 2D model provided a better prediction of the deflected shape in the longitudinal direction. However, in the transverse direction the 2D model also under predicted the observed displacements, despite the deflected shape appearing to be a better match.

Finally, the 1D model was adjusted to allow for soil structure interaction (SSI) via a rotational spring at the base. The stiffness of the spring was calculated based on CPT tests performed in the area, and empirical equations. This adjustment allowed the predicted transverse displacement to significantly increase so that it could provide a better match to the observed data. The percentage of roof displacement caused directly by the rotation at the base was equal to about 10% in the longitudinal direction and 30% in the transverse, consistent with previous forced-vibration testing.

ACKNOWLEDGEMENTS:

The authors would like to acknowledge GeoNet for implementing the instrumentation program and Hamish Avery for assistance with the recorded data. Grateful acknowledgement is also due to Jeff Clendon for providing the structural plans for the building and the data from CPT testing.

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