EARTHQUAKE ENGINEERING IN AUSTRALIA – International Collaborations and Future Directions

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Abstract

This paper highlights the key issues faced by earthquake engineers working in low seismicity regions such as Australia and how some of the research I have been involved with has benefited from collaborations with researchers from the JRC in Ispra, the University of Pavia and the University of Rome in Italy. In particular, 3 collaborative projects that I have been involved with will be discussed. These deal with: (1) the seismic assessment of older concrete frames with and without brick masonry infill walls; (2) the seismic strengthening of concrete columns in soft-storey frames to increase displacement ductility; and (3) the seismic behaviour and assessment of unreinforced brick masonry buildings.

INTRODUCTION

By world standards, the earthquake hazard in Australia is comparable to much of Asia, eastern Europe and central and eastern North America (refer Figure 1). The effective peak ground acceleration coefficient used for seismic design in Australia ranges from 0.05g to 0.11g over most of the continent, with 0.08g applied in both Sydney and Melbourne where nearly 50% of the nation's population is concentrated.

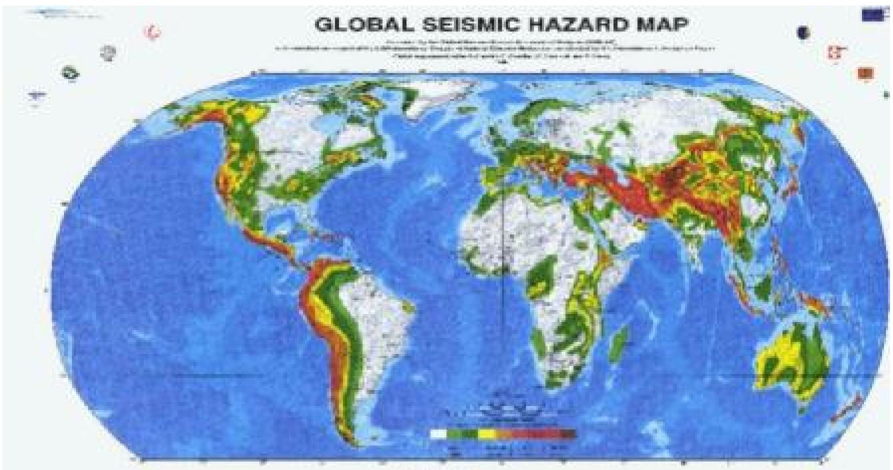


Figure 1 – Global seismic hazard map (from Giardini et al, 1999).

While the earthquake hazard is comparatively low in Australia, the vulnerability of buildings to earthquake effects is high. This is largely due to the widespread use of gravity load dominated reinforced concrete (RC) frames and, more significantly, unreinforced masonry (URM) construction. The URM construction is comprised mainly of low to medium-rise buildings, many of which are for domestic use. Australian research to date suggests that most URM buildings, if well built and not badly deteriorated over time, should survive the "design magnitude" earthquake (500 year return period with EPGA ≈ 0.1g). Most concrete structures will also behave satisfactorily during a "design magnitude" earthquake (DME). For example, shake table tests on a 1/5-scale RC frame at the University of Adelaide indicated that a "code-compatible" RC frame would respond "elastically" under the DME. Figure 2, which shows the maximum base shear versus the peak shake table acceleration recorded during the series of tests, suggests that the structure only began to respond inelastically at base shear levels in excess of 25% of the weight of the structure. This was confirmed with an experimental static pushover test that was conducted on the frame after all dynamic testing was completed.

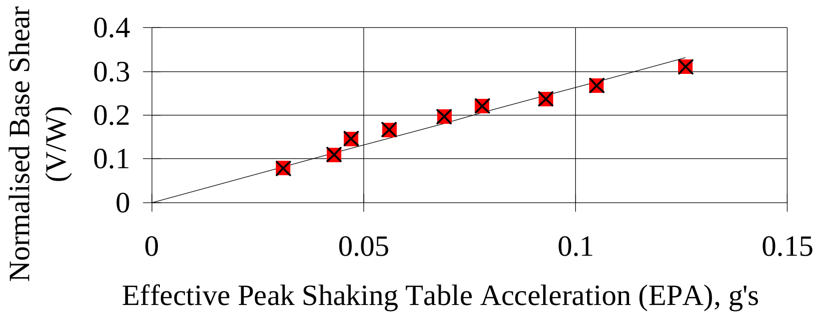


Figure 2. Shake table test results for 1/5-scale 3-storey RC frame (Griffith and Heneker, 1995).

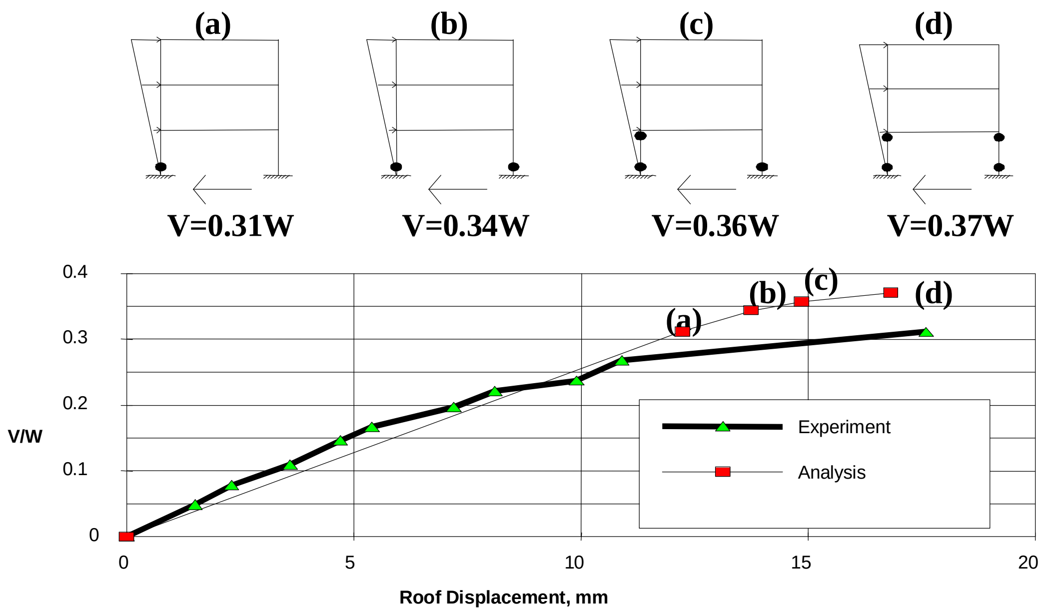


Figure 3. Static pushover of 1/5-scale 3-storey RC frame (Griffith and Heneker, 1995).

The data, plotted in Figure 3, shows again that the structural response does not become significantly non-linear until quite large base shear is reached – well in excess of the 4% - 6% normally used in design checks by assuming an inelastic response modification factor (R_f) of 4 (for non-seismic concrete frames). The overall lateral drift was only 0.9% (corresponding to a roof displacement of 18 mm when collapse was imminent) although in the bottom storey where most of the deformation occurred the effective storey drift was roughly 2.5%. Thus, while both URM and RC frame construction appears to have the seismic capacity to resist the DME, there is little doubt that a bigger than expected earthquake (e.g. a 2000-year return period event) will place significant inelastic demands on both of these forms of construction.

This begs the question as to what is the chance of a bigger earthquake, say in excess of 0.3g. Figure 4, taken from Paulay and Priestley (1992), suggests that for low seismicity regions there is a big increase in acceleration for small increases in return period in the 500 to 2000 year return period range. It is unlikely that much ductility exists to save these structures in an overload situation. This raises an important question – should Australia be designing for longer return period earthquakes?

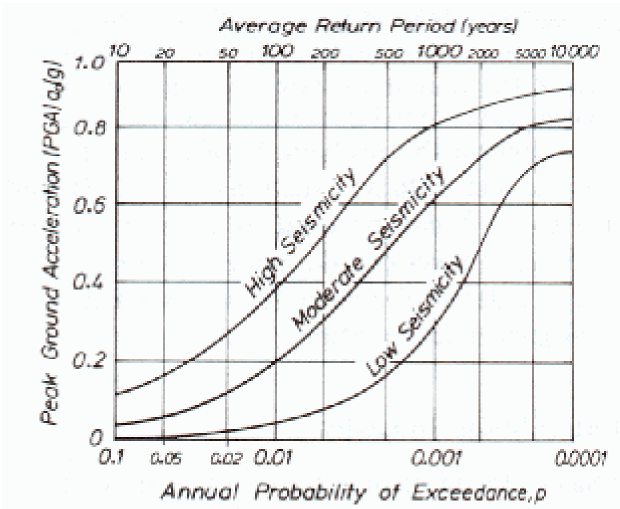


Figure 4. Relationship between PGA and annual probability of exceedance for different seismic regions (from Paulay and Priestley, 1992).

INTERNATIONAL COLLABORATIONS

In this section, three areas of research activity will be described that involve significant international research collaborations. Each of these activities has been facilitated to a large extent by the initial work conducted on R/C frames with masonry infill by staff (and the author) at the European Laboratory for Structural Assessment (ELSA) at the JRC in Ispra, Italy. The contacts made with other European earthquake engineers during the author's 5 month period working at ELSA on that project enabled further collaborations on the topics of composite retrofit of RC columns/frames and the seismic behaviour of URM buildings. The collaborative nature of these projects is described below.

R/C frame + URM infill project

In this EU funded project, two full-scale, 4-storey reinforced concrete (RC) frames were constructed for testing by ELSA staff at the JRC, Ispra. One frame was tested as a bare frame; the second frame had unreinforced masonry infill placed in each bay of the 3-bay, 4-storey RC frame structure. Figure 5(a) shows the two frames after they were positioned in the laboratory adjacent to the reaction wall.

Figure 5(b) shows a close-up view of the damage to one of the infill walls at the ground floor after initial testing. Further details can be found in Pinto et al (2002). Results, in the form of ground floor shear versus storey drift is shown in Figure 6 for both the frames with and without infill where it can be seen that the infill strengthened the frames by almost 400%. Furthermore, the RC frame reached its peak strength at a lateral drift of about 0.5% while the infill frames maximum strength was attained at a drift of about 0.1%.

(a) overview of ELSA RC frames.

(b) damage to URM infill in ELSA RC frame.

Figure 5 – Full-scale RC frame tests at ELSA facility at JRC, Ispra.

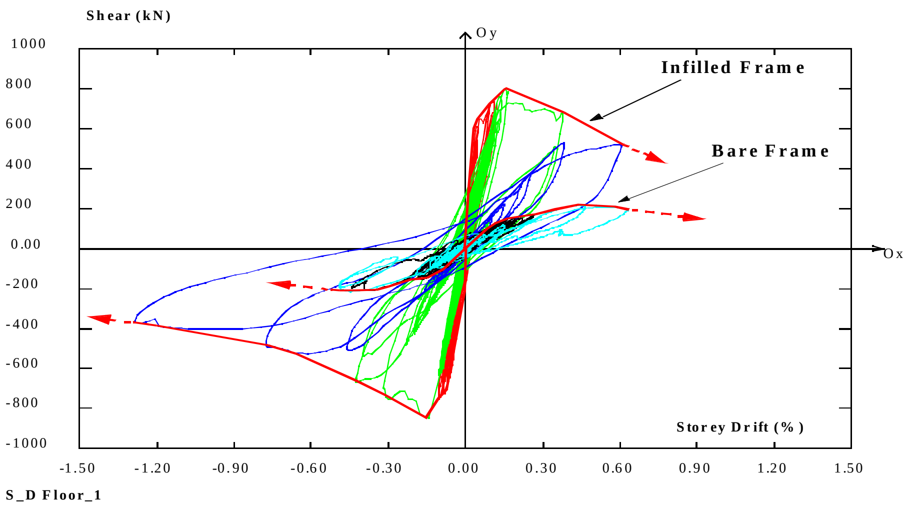
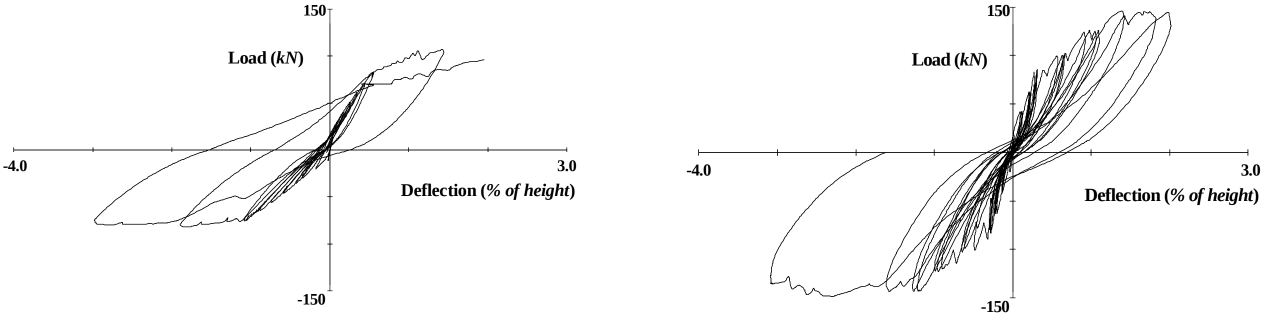


Figure 6 – Storey shear versus drift for ELSA test frames (from Pinto et al, 1999).

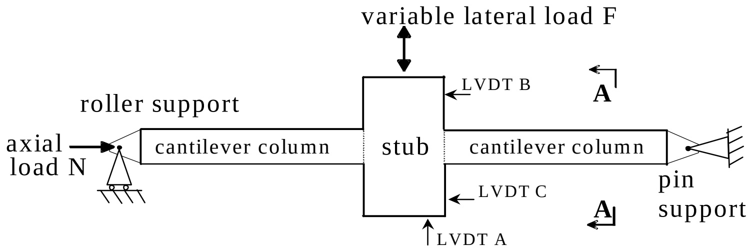
In tests at Adelaide, the ductility of typical Australian RC frames and columns has been shown to be extremely limited. Figure 7(a) shows the load-deflection curve for a ½-scale concrete frame without URM infill subjected to quasi-static cyclic loading. The beam-column joint failed at about 1% drift without showing any significant signs of inelastic response beforehand. As with the ELSA tests, the frame with infill was stronger than the bare frame (refer Figure 7(b)), although in this particular case only 50% stronger.

A similar result was observed in quasi-static tests conducted on RC columns where the column strength was reached at drifts of about 1.5% with little usable ductility exhibited during static and cyclic tests (Figure 8). Clearly, such frames in Australia may well suffer complete collapse during a bigger than expected earthquake.

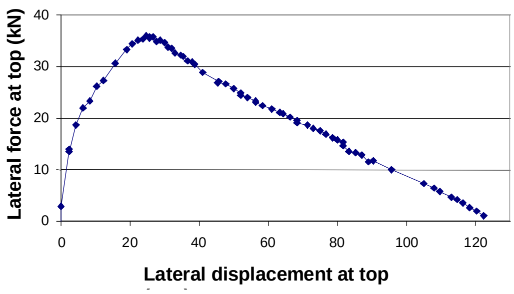


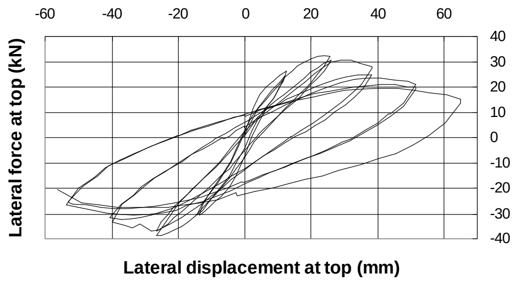
(a) Storey shear versus drift (no infill) (b) Storey shear versus drift (with infill)

Figure 7. Test results for ½-scale r/c frame subject to cyclic loading (from Griffith and Alaia, 1997).



(a) Schematic of column test configuration





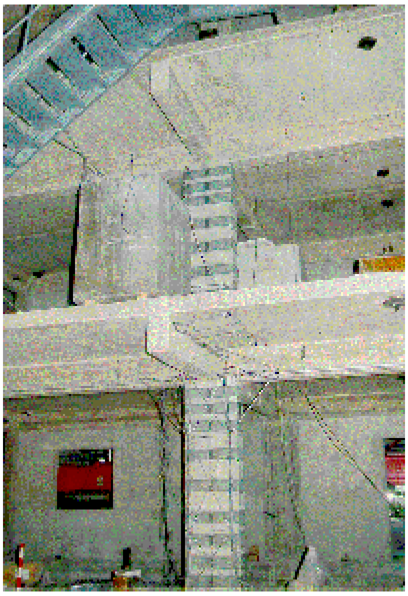
(b) Monotonic static test of r/c column. (c) Cyclic test of r/c column.

Figure 8. Test results for 200x200mm R/C column (Wu et al, 2001).

Composite retrofit of RC columns

One of the outcomes of the JRC/ELSA tests on the two RC frames discussed above was that several seismic retrofit strategies were subsequently applied and tested. Of these, two specifically addressed concrete columns using either (a) metal straps wrapped around the columns in the region of maximum bending moment to improve column displacement ductility (Figure 9(a)); and (b) metal jacketing plus additional concrete to increase the strength and ductility of the column cross-section (Figure 9(b)).

In Australia, there are many examples of weak column-strong beam frames that have been designed primarily to resist gravity loads and, as shown earlier, have only nominal lateral strength and ductility. Thus, following on from the JRC/ELSA research, a small research project commenced in 2000 at Adelaide to see if it was possible to improve a rectangular concrete column's strength and/or ductility using composite interaction without relying on complete jacketing to achieve improved confinement. The reason for this is because of difficulties in achieving effective confinement in columns with rectangular cross-sections. The system considered at Adelaide employed steel plates which were bolted to the flexural faces of the column and, due to the end boundary condition, only attracted a compressive force in the segment between the first bolt and the beam/column joint (refer Figure 10). Hence, the compression plate delayed crushing of the concrete and was shown experimentally (also numerically and analytically) to be capable of substantially increasing ductility and/or strength. The cyclic load deflection test data is shown in Figure 11 where it can be seen that the plated column (specimen 4ACP6) had more strength and improved post-peak load behaviour than the bare RC column (specimen 3ACR). Specimen 4ACP6 had 6mm thick steel plate bolted (without adhesive) to the column compression and tensions faces. Photos of the test specimens at the conclusion of testing are presented in Figure 12. Complete details can be found in Wu, Griffith and Oehlers (2003).



(a) ductility retrofit of RC columns

(b) strength + ductility retrofit of RC columns

Figure 9. Seismic retrofit of columns in ELSA frames.

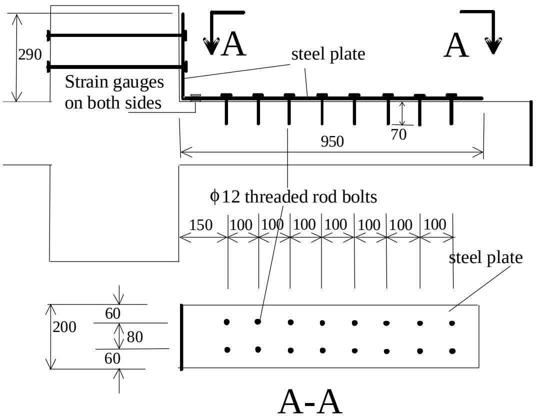


Fig.10 Details of partial interaction plating

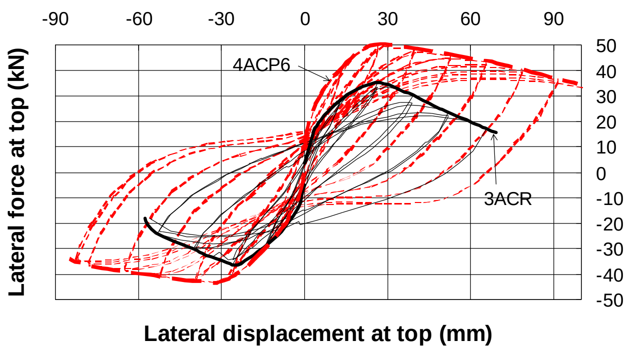


Fig.11 Cyclic test results

Based on the promise exhibited by this alternative retrofit scheme, collaborative work commenced in 2001 with Professor Monti from the University of Rome to model the composite behaviour using the research finite element analysis tool, FedeasLab. To date, two post-graduate research students from the University of Rome have spent extended periods working at Adelaide on this research. A conference paper is currently in preparation to report on the behaviour of concrete frames retrofit in this manner. An application for follow-up funding is in preparation to study this system when subjected to bi-directional loading and the possible use of FRP instead of steel plating.

(a) 3ACR (Δ=-56~65mm) | (b) 4ACP6 (Δ=-82~150mm) | (c) 4ACP6 at +150mm

Fig.12 Conditions of the cyclically tested specimens (from Wu et al, 2003).

Seismic behaviour or URM buildings

Another area of collaborative research activity to follow from the author’s work at ELSA concerns the seismic response and design of unreinforced brick masonry construction. In Australia, it appears that URM construction can be made to “work” under the DME (due to over-strength, not ductility) but little or no capacity exists to cope with a larger seismic event. Work is in progress to attempt to better estimate the seismic demands, in terms of displacements, that are likely during Australian earthquakes. This information, when used in conjunction with a displacement-based method of assessing the seismic capacity of URM walls subject to out-of-plane motion (Doherty et al, 2002) will enable engineers to make better judgements as to just how much (or little) reserve seismic capacity exists in Australian URM construction. Of interest here is that this work attracted the attention of Italian researchers who saw the potential for use of a displacement-based assessment method in the performance of regional seismic risk assessment in Italy.

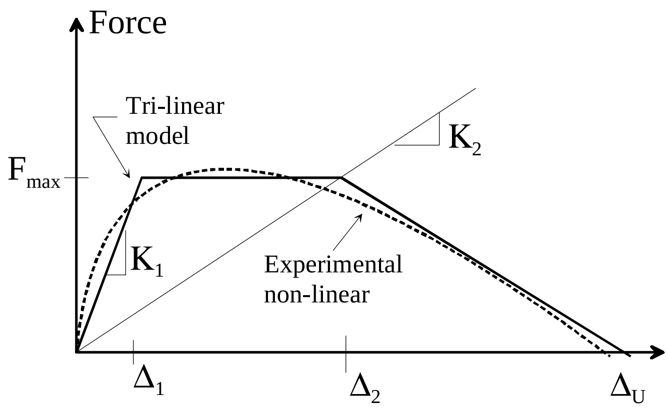
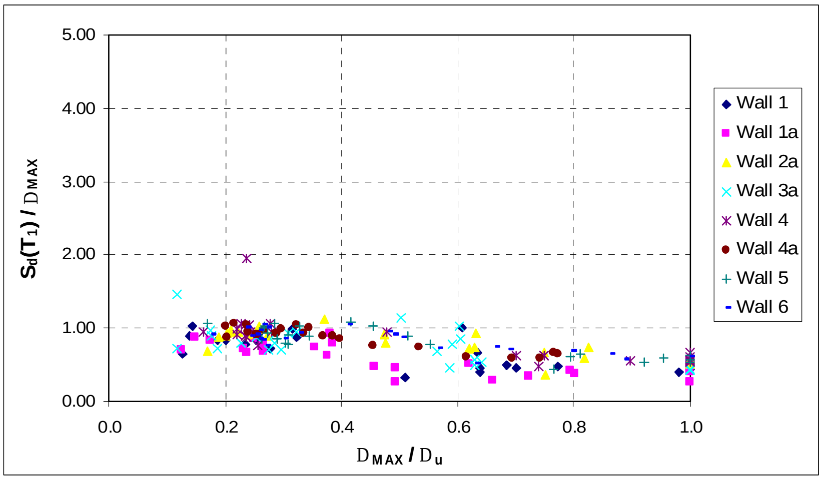
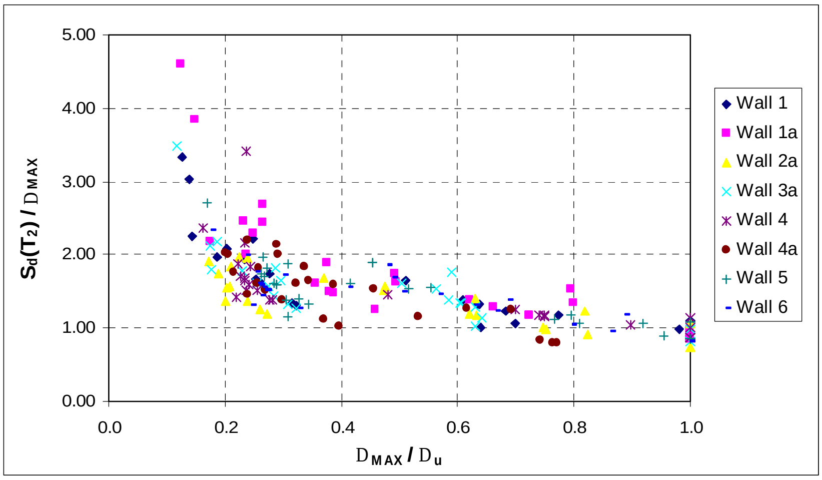


Figure 13. Force-displacement relationship of URM wall.

In work with Magenes from the Rose School at The University of Pavia, the author verified the accuracy of predicting the maximum response, Δ_{max}, of a masonry wall in vertical bending using a 5% damped displacement response spectrum with a period of T_1 and T_2 corresponding to the stiffnesses K_1 and K_2 shown in Figure 13, respectively. The results are shown in Figures 14 (a) and (b) where it can be seen that using the initial linear elastic stiffness K_1 (and corresponding period T_1) that good estimates of the actual maximum wall displacement Δ_{max} are obtained when the maximum displacement is less than 50% of Δ_U (refer Figure 14(a)). On the other hand, when the max displacements are greater than 50% Δ_U, better estimates are obtained using the stiffness, and period, going through the trilinear curve at Δ_2 (refer Figure 14(b)). This result was confirmed using 8 different accelerograms and a wide range of wall geometries and boundary conditions (refer Griffith et al, 2003) as shown in Table 1 where the mean error using T_2 was only 2% greater than Δ_{max} when $\Delta_{max} > 0.5\Delta_U$ as opposed to the mean estimates using T_1 when $\Delta_{max}>0.5\Delta_U$ which were 49% less than the actual maxima.



(a) Response spectrum predictions using T_1 values for period.



(b) Response spectrum predictions using T_2 values for period.

Figure 14. Assessment of prediction of maximum displacement from elastic displacement spectrum using different effective periods. Artificial accelerogram, all walls (from Griffith et al, 2003).

Table 1. Mean and standard deviation of the error $\mathrm{Err}(T)=[S_d(T)-\Delta_{max}]/\Delta_{max}$ using different definitions of effective period, for all walls and all accelerograms (from Griffith et al, 2003).

Displacement range	$\mathrm{Err}(T_1)$	$\mathrm{Err}(T_2)$	$\mathrm{Err}(T_S)$	
$50\%\Delta_U > \Delta_{MAX} > 0$	-17%	125%	61%	mean
	24%	152%	47%	st. dev.
$\Delta_{MAX} > 50\%\Delta_U$	-49%	2%	51%	mean
	19%	25%	74%	st. dev.
$\Delta_{MAX} > 70\%\Delta_U$	-53%	-5%	47%	mean
	19%	20%	69%	st. dev.

The outcome of this research is that the use of a simple tri-linear force-displacement curve can be used to describe the "capacity" of a URM wall subject to vertical bending. This curve could be used in conjunction with a "demand" curve in a capacity spectrum approach for use in conducting seismic risk assessments on a regional basis where buildings would be checked first to ensure that no out-of-plane failure occurred before then considering the overall building response which would be governed by the in-plane response of URM walls. Collaborations on this topic are continuing to extend the methodology for use in walls where bi-axial (two-way) bending takes place.

FUTURE DIRECTIONS

It should be clear by now that URM and RC construction are of primary interest to earthquake engineers in Australia. The areas of research priority, in my opinion, should be in two broad areas:

- the assessment of the seismic capacity of URM and RC structures; and
- the development of appropriate seismic retrofit strategies for both of these forms of construction.

As noted earlier, current research collaborations are underway with Magenes to develop improved building capacity curves for use in regional seismic risk assessment models for URM buildings accounting for out-of-plane failure modes as well as in-plane wall/building response. Collaboration is also occurring with Monti to develop improved analytical models for RC members that have been seismically retrofit using FRP and steel plating and jacketing. These and many other areas of activity, however, require attention. For example, the seismic response of non-seismic detailed RC buildings is still not well understood where moment frames carry gravity loads and shear walls resist lateral wind/earthquake loads. Gaining an improved understanding of how URM and RC structures respond during earthquake motion will enable us to develop more efficient seismic retrofit and strengthening techniques.

CLOSING REMARKS

Earthquake hazard in much of Europe, North America and Asia is similar to that in Australia. Hence, there are many similar seismic design and risk issues that make international collaboration attractive and potentially of benefit to all. The international collaborations discussed in this paper have already proven to be exceptionally useful in advancing the practice of earthquake engineering in Australia. Given the fierce competition for research funding in Australia (no doubt overseas too), making the most of our research through logical international collaborations on topics of mutual interest makes sound economic sense.

ACKNOWLEDGEMENTS

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REFERENCES:

Doherty, K., Griffith, M.C., Lam., N. and Wilson, J. 2002. "Displacement-based analysis for out-of-plane bending of seismically loaded unreinforced masonry walls," *Earthquake Engineering and Structural Dynamics*, John Wiley and Sons, Vol. 31, No. 4, pp. 833-850.

Giardini, D., Grünthal, G., Shedlock, K. and Zhang, P. 1999. "Global seismic hazard map," produced by the Global Seismic Hazard Assessment Program, Swiss Seismological Service, Zurich.

Griffith, M.C. and Heneker, D.G. 1995. "Implications of Earthquake Simulator Test Results for the Aseismic Design of Reinforced Concrete Frames," *Proceedings, Pacific Conference on Earthquake Engineering*, Melbourne, Vol. 2, pp. 41-48.

Griffith, M.C. and Alaia, R. 1997. "Gap Effects on the Seismic Ductility of Brick Infilled Concrete Frames," *Proceedings of the 15th Australasian Conference on the Mechanics of Structures and Materials*, Melbourne, pp. 305 – 310.

Griffith, M.C., Magenes, G., Melis, G. and Picchi, L. 2003. "Evaluation of out-of-plane stability of unreinforced masonry walls subjected to seismic excitation," *Journal of Earthquake Engineering*, Vol. 7, Special Issue No.1, pp. 141-169, (2003).

Paulay, T. and Priestley, M.J.N. 1992. "Seismic design of reinforced concrete and masonry buildings," John Wiley and Sons Pty. Ltd., New York.

Pinto, A.., Verzeletti, G., Molina, J. and Varum, H. 1999. "Pseudo-dynamic tests on non-seismic resisting RC frames (bare and selective retrofit frames," ICONS – Topic 2: Assessment, Strengthening and Repair, Joint Research Center, Ispra.

Pinto, A.., Varum, H. and Molina, J. 2002. "Experimental assessment and retrofit of full-scale models of existing RC frames, *Proceedings of the 12th European Conference on Earthquake Engineering*, Elsevier Science Ltd., Paper Ref. 855.

Wu, Y.F., Griffith, M.C. and Oehlers, D.J. 2003. "Improving the strength and ductility of rectangular reinforced concrete columns through composite partial interaction: Tests," *Journal of Structural Engineering*, ASCE, Vol. 129, No. 9, pp. 1183 – 1190.

Wu, Y.F., Oehlers, D.J. and Griffith, M.C. 2001. "Composite Plated Columns," Proceedings of International Conference on *FRP Composites in Civil Engineering*, Vol. 1, J.-G. Teng (Ed.), Elsevier Science Ltd., pp. 767-774, (2001).