

## Improving Linkages Between Earthquake Engineering

### Research and Practice

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**ABSTRACT:** Researchers, funding agencies, practicing professionals, end users and owners are often frustrated with the protracted process from research to practice. From the inception of new ideas, concept development, basic and applied research, product development, codification to final mainstream practice, considerable time is needed for success. For earthquake engineering, this is especially true due to the broad nature of the discipline. To help understand this process from research to practice, three simple behavioural models are given: series, parallel and open market. These models are explained by critical review of seven case studies. For a successful transition from research to practice it is shown that a collaborative engagement between academia, the design professions and industry is necessary. It is concluded that for new ideas to be mainstreamed into general practice, enhanced undergraduate programmes are needed along with design professionals that can also teach and conduct basic research across the many facets of earthquake engineering.

### 1 INTRODUCTION

In many fields of professional engineering, individual researchers, funding agencies, practicing professionals, end-users, and owners are often perplexed about the long drawn-out time frame needed to develop new ideas from research to practice. This is especially the case for earthquake engineering due to the multidisciplinary nature of the discipline. Earthquake engineering transcends the boundaries from basic earth science, professional engineering (which itself is both science and art), through the emerging areas in the social sciences and humanities. Considerable time is needed to successfully take new ideas from concept development, to basic and applied research, product development, codification, and finally through to mainstream practice. To help understand the process from research to practice, this paper presents three simple behavioural models: series, parallel and open market. These models are explained by critical review of seven case studies: Capacity Design; Seismic Isolation; Structural Control; SAC; PRESS; HAZUS; and the emerging field of performance based earthquake engineering. It is shown from the most successful cases from research to practice that earthquake engineering is a collaborative engagement between academia (both research and teaching), the design professions (consultancies) and industry (construction, materials and manufacturing). Finally, several conclusions and practical solutions are suggested to help progress new ideas from the research phase to become mainstreamed into general practice.

## 2 RESEARCH BEHAVIOURAL MODELS: FROM RESEARCH TO PRACTICE

This section describes three models that can be used to idealise and understand the behavioural patterns and interaction between the major players in the research enterprise. But before the models are presented it is essential to define the major players. These reside in three almost disparate communities and are defined as follows:

- *Research Community*: This consists of both academic researchers as well as public/private research providers. The former reside in major research universities, while the latter comprise Crown Research Institutes (for example Geological and Nuclear Sciences (GNS) in New Zealand) and National Laboratories (for example Lawrence Livermore and Brookhaven in the US) and non-governmental agencies (such as the Building and Research Association (BRANZ) in New Zealand, and SRI in the US)
- *Design Community*: The design community is a professionally educated engineering workforce that provides services (that embodies facets of earthquake engineering expertise) to the industrial community. The design community keeps pace with new developments in two ways: First by hiring fresh university graduates, which (presumably) have all the latest thinking at their fingertips. Secondly, seasoned professionals engage in short refresher courses, conferences, and sometimes code committees. On rare occasions they may provide input into research teams.
- *Industrial Community*: The industrial community consists of material suppliers, construction (general) contractors, and specialist subcontractors that include manufacturers of specialist fittings and devices. The industrial community either embraces or spurns new technology depending on whether it will give them a competitive advantage. Certain subcontractors may engage in their own research and development activities. While the industrial community is served by the professional (design) community, it tends to be divorced from the research community.

From the conception of new ideas to their implementation is discussed using some analogies to the mechanics of structural systems.

### 2.1 Series Model

Fig. 1 presents a sequential series of research related activities. This is the simplest form of research model; it tends to occur by default without any prior planning. The principal advantage of the series research model is freedom. Researchers in a series-type environment are not bound to collaborate with the communities they serve—indeed such collaboration may be considered as an impediment to progress. The principal disadvantage of this model is the uptake time. Typically each of the three major activities (from research to design practice and then construction) may each take some 5 years leading to overall durations in excess of 15 years from the inception of the research activity until the results become a mainstream norm. This approach is generally not efficient; research results may be out-of-date and/or superseded by other events prior to uptake. Notwithstanding, due to the inherent scepticism and/or conservatism of principal stakeholders that initially resist buy-in, for very fundamental and revolutionary ideas a series model approach of conducting research is often inevitable.

To obtain “uptake” of research, technology transfer to the design profession is key to success in the series model. Uptake within consultancy practices must rely on a core of well-informed, well-educated engineers who have kept up-to-date in their knowledge by reading the literature and attending conferences. Nevertheless, it is often a risky business to be the first to implement new solutions. It is for this reason that uptake often slows through the approvals stage.

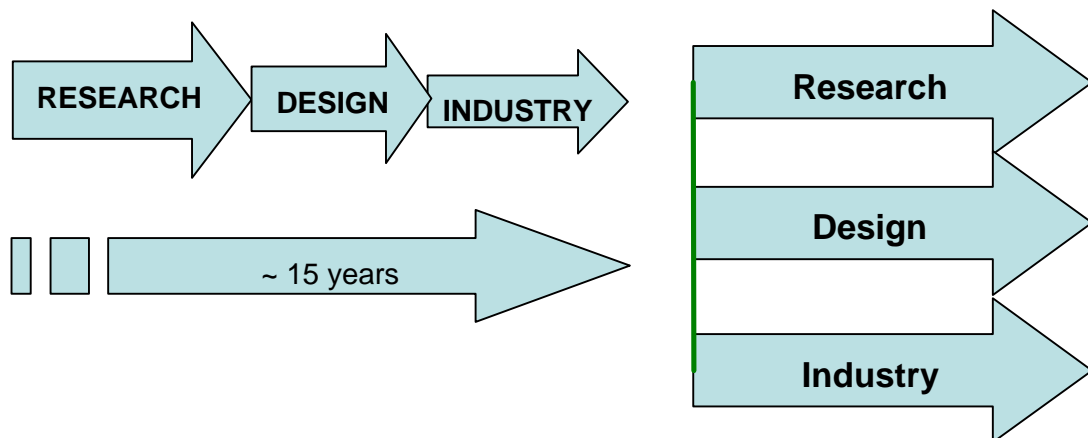
The construction industry must also be convinced that any new ideas or technology lead to feasible, constructible and competitive solutions. If the construction industry is not convinced, then it is likely

that the financial (banking) community will also become hesitant to lend money to “risky” new ventures. If the construction industry becomes hesitant, then this is hedged against conservative tender bids, rather than an aggressive bid based on well-known trends in construction practice.

One of the major delays in the series model occurs when the research is essentially complete, but requires codification before widespread acceptance leads to mainstream application. This step alone may take in excess of 10 years.

To summarise using a structural systems analogy, the “series” research model is

- (i) unstable when pushed and can buckle under pressure
- (ii) only as strong as the weakest link in the chain
- (iii) a simple (non-redundant) system—if any link fails the system and hence the research enterprise has essentially failed.



**Figure 1 Models from research to practice: Series model left; Parallel model right.**

## 2.2 Parallel Model

Much research is an evolutionary process where various degrees of collaboration exist between the stakeholders. If the principal stakeholders can identify a common problem then the research can be conducted in a parallel fashion. This is essential if the research uptake time needs to be minimised. Other than the research providers, the principal stakeholders (the design and industrial communities) each need to be convinced of the research needs in their own minds to form a tightly knit collaborative team.

Moreover, to minimise uptake, it is essential that the codification of new techniques, materials and processes closely follow the research with a minimal lag time. For this reason, the main users of the research, the designers and consulting practitioners, lead this initiative. Ideally, these members should be seen to be equal partners of the research team, not an adjunct to it. Although code writing bodies tend to be represented by a wide variety of stakeholders, many members are volunteers and the rewards for bringing a code to the market place are too intangible. However, if several research team members are also on the code committee, then the general lethargy regarding new ideas can be negated.

To return to a structural analogy, the “parallel” model is:

- (i) a redundant system—there can be several paths to success and the load can be shared and carried in many different ways.
- (ii) with several parallel links a more stable system is created; the likelihood of any one member buckling under pressure is diminished.
- (iii) overall a more robust and stronger system; the whole is as strong as the sum of the parts.

### 2.3 Market Forces Model

Bruneau and Tierney (2002) have recently described an open-systems approach that uses market-based metaphors to conceptualise the loss-reduction process. Their methodology is used by the US National Science Foundation (NSF) Engineering Research Centers (ERC) directorate to provide targeted funding to the Multidisciplinary Center for Earthquake Engineering Research (MCEER) headquartered at the State University of New York (SUNY) at Buffalo. Their open-systems methodology is particularly targeted at bringing “new technologies” to the market place.

Bruneau and Tierney (2002) claim that “new technologies may well offer the promise of enhanced level of seismic safety, but unless those technologies are well aligned with market participants, they will not be used”. This appears to be an attempt to have bottom-up initiatives driving the market place. That is where new devices can be sold as a panacea.

Bruneau and Tierney (2002) go on to state that “research activities can advance the state-of-the-art without necessarily improving the state of practice or having other tangible effects beyond the research community. To have an impact, research activities must be linked to trends and events in the broader society and, more specifically, to fluctuations in LRM (loss-reduction market) receptivity and resistance”. Although this statement appears true, it also begs the question: Why not collaboratively set the big picture (top-down) and via systematic research fill in the detail gaps?

It is considered that although the approach advocated by Bruneau and Tierney (2002) has considerable merit, it is too soon to see if the approach will succeed. The approach seems overly cumbersome and appears to be conceived as a means of satisfying ERC funding requirements. Such heavy handed leading of details is not considered conducive to creativity.

To return to a structural analogy, the Bruneau-Tierney market forces model can be summarised as follows:

(i) a complex system that seeks to resist the imposing forces from the marketplace and funding agency in a way that requires the least internal resistance.

(ii) Market forces dictate demand, and it is assumed that

$$\{solution-demand\} \approx \{solution-capacity\}.$$

Therefore: research intervention is needed based on the demand for new solutions.

(iii) the entire system (solution) will work well if the inputs into the complex system work well, and these inputs can actually be defined.

Regarding the latter, this is considered to be somewhat of a fallacy—it is like designing new and robust connections for a structure, but before the final form of the new structural system have been conceived.

## 3 FROM RESEARCH TO PRACTICE: SOME CASE STUDIES OF SUCCESSES (AND FAILURES)

### 3.1 Capacity design

The idea of “Capacity Design” had its roots in professional practice in the early 1970’s in New Zealand, see for example Park and Paulay (1975). Capacity design was conceived as a deterministic method for apportioning relative strengths to members. For example, consider the moment capacity of beams and columns at a beam-column junction such that

$$\phi M_n > \lambda M_o$$

in which  $M_n$ = nominal moment capacity to be provided for the column under consideration;  $M_o$ = provided strength of the beam based on a realistic (expected) reinforcing steel stress;  $\phi$  =

undercapacity (resistance) factor ( $\phi < 1$ ); and  $\lambda =$  overstrength factor ( $\lambda > 1$ ). Strictly  $\phi$  and  $\lambda$  are probabilistic in nature, but in the absence of refined knowledge are allocated values in a pragmatic way to ensure successful response under the most adverse circumstances. This theory, in essence, forms the basis of the so-called strong-column/weak-beam concept.

Because of its pragmatism, the ideas behind capacity design were verified by a limited degree of analysis but substantiated extensively by large scale experimentation on components and sub-assemblages. In New Zealand the design profession, particularly the former consulting arm of the government, the now defunct Ministry of Works and Development (MWD), also had a significant part to play. In addition to conceptual developments and codification of research, there was a rapid prototyping of new structural systems that embodied structural details required by “Capacity Design” thinking.

Hindsight now shows that the New Zealand research associated with the subject of “Capacity Design” was an informal team effort. What started as classical single investigator series research was quickly converted into a “parallel” system of research and code development activities. Here the researcher providers (mainly the Universities of Canterbury and Auckland) closely collaborated with designers such as the MWD, and several private sector consultancies.

As much of the construction at that time (1970’s and 80’s) was for public works, a heavy hand was exercised by the MWD resulting in little resistance in the field implementation of more complex construction details by their private sector construction contractors.

### 3.2 *Seismic Isolation*

The need for seismic isolation in New Zealand arose when a new railway viaduct over the Rangitikei river was required as part of the Mangaweka deviation. The deviation was part of route improvements that were required to bypass several under-size tunnels, sharp radius curves and aging bridges. The 70 m tall South Rangitikei rail bridge was initially conceived as a continuous structure with A-frame piers that possessed yielding pins at the base of the columns.

The final design by private sector consultants was based on analytical research conducted by the government’s Department of Scientific and Industrial Research (DSIR). This led to the development of “stepping” piers that consisted of twin columns, each resting on torsional beam mechanical energy dissipaters. Although conceived in the 1960’s, the bridge construction was ill-fated, consequently the Mangaweka deviation did not open for rail traffic until 1981.

Meanwhile, these events spurred on other seismic isolation endeavours with several MWD highway bridges (Toi Toi, Bolton St) and state-owned buildings (William Clayton) being isolated with an assortment of new devices. The performance of these devices, including the lead-rubber bearing, lead extrusion dampers and other metallic mechanical energy dissipaters were well investigated by the pioneering researchers of the now defunct DSIR. Many of these developments can be traced in the book by Skinner et al (1993).

Interestingly, most of these new developments did not take place within the Universities due to a tight collaboration between the conceivers (researchers at the DSIR) and the owner/designer/contractor (MWD). Thus a simple parallel research system was born. Similar private sector developments also took place, but on a reduced scale.

Most of the seismic isolation research that took place in 70’s and 80’s, did so in the absence of formal design codes or standards. Innovative new designs were implemented by very skilled and experienced engineers in a stable and buoyant work environment.

Although the field of seismic isolation has matured over the past three decades, it is of interest to note that new developments have stalled. It is considered that there are several reasons for this:

- (i) There have not been formal undergraduate education programmes at the Universities that teach the fundamentals of isolation through design projects—it is still considered an alternative, not mainstream activity.

- (ii) There have been several engineering schools that from time to time teach graduate courses in seismic isolation. But teaching of seismic isolation remains at the graduate level—it is destined to remain an elitist, rather than mainstream, activity.
- (iii) There is a general absence of codes for isolation design.
- (iv) For the codes that do exist, these tend to place overly onerous demands on isolation hardware. Generally, codes require all prototype bearings to be individually tested, adding considerable (and unnecessary) cost to the products.

Regarding the latter, it is interesting that plastic hinge zones in prototype reinforced concrete structures are not tested at all; the concept is known to work through rigorous laboratory experimentation and analytical modelling. The fact that codes require relentless testing of isolation hardware indicates an implicit and ill-founded mistrust of the research base from which seismic isolation was developed.

### 3.3 *Structural Control*

There is a continuum of structural control methods from active, semi-active, to the aforementioned passive (seismic isolation). This section will discuss the genesis of active and semi-active control.

Although the idea of controlling civil structures in an active way is not new, modern structural control is generally considered to have its roots in mechanical and aerospace engineering. Its adaptation to civil structures and earthquake engineering applications dates back some two decades where active mass damping and active tendon bracing was first considered.

Much of the concept development was carried out in the United States by Soong and his co-workers. See for example Soong et al (1991) and Reinhorn et al (1993). Large scale experimentation verified the concepts first in the laboratory (at SUNY at Buffalo) and then on a prototype experimental structure in Japan. This was a “parallel” systems research activity: a partnership between academia (US) and industry (Japan). In contrast with their mechanical and aerospace counterparts, full active control of civil structures has often been criticised for having unwieldy external electric power demands that is necessary to actively move heavy concrete and/or steel buildings or bridges in earthquakes. Moreover, given that NASA with its well endowed research budgets has all but abandoned active control of its very lightweight space structures, the promise of seeing widespread use of actively controlled civil structures seems even more remote in the foreseeable future.

It is thus more likely that a hybrid type of control (a combination of active and passive control theories), or so-called semi-active control, will continue to see more interest in the future. Semi-active control seeks to control the seismic energy distribution in a structure without the need of a large external power source. Indeed, semi-active control can be powered by low-voltage batteries; only low-power demand switching devices and orifices need controlling.

There are several fronts for which semi-active control is being undertaken. In the United States there is collaboration between university researchers and device, switching and servo-controller manufacturers. However, this is a marriage of convenience to fulfil so-called post-cold war US governmental “peace dividend” requirements. This is seen by many critics as an unnecessary form of corporate welfare.

It could be said that this is a weak “parallel” system research. There are two missing ingredients: the design profession; and the construction industry. Therefore, it is contended that active control research is not really driven by need; rather it is two sectors of the research community (academia and device manufacturers) engaging in a marriage of convenience. Because of its relative infancy, semi-active control will remain a fruitful research topic for some time, but it is unlikely to be brought into the mainstream of civil, structural or earthquake engineering practice. Many practitioners, due to a lack of ownership of the problem, consider control to be a nice and fanciful notion—a method of solutions looking for a problem.

### 3.4 SAC

As a result of numerous failures observed in structural steel moment frame connections in the 1994 Northridge earthquake, a tripartite consortium was born: SAC. This stands for SEAOC (Structural Engineers Association of California), ATC (Applied Technology Council, a non-profit industry group) and CUREE (California Universities for Research in Earthquake Engineering). SAC appears to be an ideal form of consortium where its parts tend to function as a “parallel” system to rapidly bring research to practice.

Funding for the SAC projects was principally derived from FEMA (the US Federal Emergency Management Agency). This is a mission-oriented agency that is not strictly in the business of doing research. Instead “topical studies” have been funded as a pragmatic means of developing the state-of-the-art. Therefore it could be argued that the investigations were not as fundamental as a purest researcher may desire. Nevertheless, the project can be seen as success as it has essentially advanced the state-of-the-art and also adjusted the state-of-practice with the advent of model codes.

In spite of the considerable funding that has been invested by FEMA and others on the steel moment frame connection problem there was still been a considerable eight-year time lapse from the 1994 Northridge earthquake until many of the final peer reviewed papers that have formed the basis of the code recommendations. See in particular Cornell et al (2002).

It is considered that one of the reasons for the success of this project was that an end goal of new consensus based code recommendations for the design and detailing of a new generation of steel moment connections was first set. With this end goal in sight, it was then necessary to build an integrated research path that incorporated advanced and simplified analytical methods together with numerous design studies. New construction methods and design details were validated with large scale experimental investigations on full size specimens. This step was essential in getting credibility between the research community and the design profession.

For this project to remain on ongoing success, it is essential that new model code design recommendations and methodologies be taught in the schools of engineering, not just in graduate courses, but also through project-based learning at the undergraduate level.

### 3.5 PRESSS

Historically the majority of seismic resistant concrete structures were designed and built using reinforced concrete that had both low concrete and steel strengths. This was in the belief that ductile behaviour of plastic hinge zones is of paramount importance, and member ductility is inversely proportional to material strengths. In non-seismic regions however, contractors were enjoying the competitive advantage of precast/prestressed concrete construction. To capture the benefits of precast concrete it was thus necessary to undertake considerable research on materials, connections, assemblies and near full size prototype structural systems. Thus in the late 1980s Precast Seismic Structural System (PRESSS) was born at the University of California-San Diego.

The PRESSS project is another example of a parallel research model where researchers collaborated closely alongside design practitioners and the construction industry.

Following the completion of the research phase, that culminated in the testing of a large scale five-storey precast concrete structure, there have been several significant structures constructed using the technology that emanated from the PRESSS research programme. See Priestley et al (2000). In the future it will be interesting to observe whether this successful US research programme enjoys ongoing success. As in the case of seismic isolation, it is possible that widespread use and further developments are likely to stall for two reasons:

- (i) Ongoing success will depend on widespread use through the use of progressive design codes. Building code development in the United States is a very slow consensus based process. It is not likely that governing codes such as ACI 318 will deliver the needed codification of design requirements in a timely fashion. This will impede progress.

- (ii) In the United States undergraduate degree programmes in engineering schools are quite liberal in their course offerings due to ABET (Accreditation Board of Engineering and Technology) requirements. Many engineering educators lament the fact that their degrees are watered down with too many non-technical liberal arts requirements. Others feel that the first degree should cover breadth and not depth. Regardless of the merits of such arguments most degree programmes teach the basics of reinforced concrete at the undergraduate level (although in many engineering schools even reinforced concrete is not a required course in their civil engineering undergraduate degree programme, but rather an elective left to the senior year). But it is rare to provide required or even elective courses in earthquake engineering and structural dynamics as well as prestressed concrete theory and design.

It is of interest to comment here on the contrasting experience of seismic resistant precast/prestressed concrete structures in New Zealand. Seismic resistant prestressed concrete structures have their roots in the early 1970's in New Zealand. Much of the pioneering work can be attributed to a series type model of research instigated by Park. Early research by his doctoral students Blakeley (1971) and Thompson (1977) led to several early examples of prestressed concrete construction. By the mid 1980's much of the construction of concrete buildings had shifted from fully cast in-situ monolithic construction to precast concrete frames (with connections) that emulated monolithic construction and precast/prestressed concrete flooring systems.

Designers were so eager to take on new and progressive forms of seismic resistant construction it was doubtful if the new systems had been adequately researched. Part of this eagerness was due to:

- (i) a progressive concrete code (NZS 3101) and
- (ii) a well-educated cadre of graduate engineers that had received some two years of depth at the undergraduate level in structural dynamics and prestressed concrete theory and design.

In parallel to advancements made in the state-of-the-practice, considerable effort was also made in advancing the state-of-the-art. However, it has been only recently that it has been realised that, like the steel moment frame situation in the United States, there have been several blind spots. This is because professional practice proceeded at a faster pace than the ongoing research could support. In particular, much concern has been expressed in New Zealand regarding the behaviour and detailing of 3D precast/prestressed concrete systems.

Although New Zealand structural researchers have rigorously validated design concepts and details through experiments on near full size specimens, limitations to the experimental infrastructure have precluded large scale tests of the five-storey PRESSSS type undertaken at UCSD. Only recently have initiatives to investigate complete 3D behaviour been undertaken. For example refer to the work by Matthews et al (2002). Results from recent experiments have demonstrated by that displacement incompatibilities in 3D frames can lead to adverse performance, this coupled with inadequate seating details of prestressed concrete floor systems can lead to catastrophic failures. This highlights the danger of practice charging ahead of the research community. Researchers end up spending unnecessary and excessive effort on retrospective research that is cleaning errors and commissions of the past rather than focusing on pushing the envelope and developing the future.

Only recently, some 15 years after the commencement of widespread use of precast /prestressed concrete, has research commenced on various thorny 3D issues of performance. Through large-scale experimentation and analysis, Matthews (2002) has demonstrated that, similar to observations arising from the 1994 Northridge earthquake, collapse of prestressed flooring units can be expected as a result of inadequate seating details with the supporting beams. This conclusion has been based on a full-scale super-assemblage test under a typical earthquake loading pattern. Figure 2 highlights the problem in the field and its experimental replication in the University of Canterbury structures laboratory. Similar findings have been observed by Lau and Fenwick (2001) at the University of Auckland.

Following the completion of Phase 1 of this research (the Matthews experiment), much of the specimen, in particular the precast concrete frames, remained intact as can be seen in figure 2. This has enabled the specimen to be reconfigured for reuse at a much lower cost than starting afresh.



Therefore, the *Phase 1* work of Matthews will be followed up by two additional phases of research. In *Phase 2*, it is proposed to investigate improved seating details for the construction of *future* standard precast concrete floor systems, and to make design and detailing recommendations for the New Zealand Concrete Standard 3101. In *Phase 3* it is planned to investigate retrofitting measures that can be applied to *existing* construction that possesses faulty seating details.

A strong “parallel” system of research activities now exists as a means of accelerating the research uptake. The research is being undertaken in conjunction with a Technical Advisory Group (TAG) made up of stakeholders from the academic, design profession, and construction/manufacturing communities. Several members of the TAG are also on the code rewrite committee for NZS3101 (the NZ Concrete Standard)



**Figure 2: Photographs of damage to precast concrete floor systems. Left shows the Meadows Apartment Building, California, as a result of the 1994 Northridge earthquake. Right shows Matthews super-assembly specimen at the completion of the Phase 1 testing. Note the specimen’s floor dropped out at a low seismic load with little damage to the surrounding frames.**

### 3.6 HAZUS

The aforementioned research initiatives have been activities concerned with providing improved design and construction practice for individual engineered structures. HAZUS is the software that drives the US national loss estimation for earthquakes and other hazards. Development of the methodology is described in Whitman et al (1997). HAZUS looks at families of structures and other engineered systems in the built environment and seeks to make broad loss estimation statements for scenario earthquake events. HAZUS is a GIS based computational platform through which loss estimation of nodes in a network are made. The computational model is quite comprehensive and examines the seismic vulnerability of houses and buildings (by census tracks), utilities, highways (specifically bridges), etc. By nature, HAZUS is a multi disciplinary tool that brings together earth scientists (hazard modelling), engineers (consequence modelling), and social scientists (epidemiology and outage consequences on communities). Although the computational tool has broad appeal and use, it tends to be predominately used by urban and emergency planners.

HAZUS, being funded in the US by FEMA, was not the product of a specific research activity per se, but rather a culmination of an applications oriented task force that uses the most advanced state-of-the-art knowledge. It could be argued that HAZUS is an end-product of a series research model where individual pieces of single-investigator research activities are drawn together under one umbrella. Although successful at the present time, one is left wondering about the future long-term viability of HAZUS. One of the difficulties of the series approach to research and development is there is little opportunity for timely feedback from users to researchers. Without such timely feedback there is neither opportunity nor incentive (via research funding) for researchers to advance the state-of-the-art.

### 3.7 PBEE

The implementation of Performance Based Earthquake Engineering (PBEE) has become a current goal of several countries. In many respects PBEE resembles the early days of earthquake engineering when issues of capacity design, detailing for ductility and dynamic analysis were the hot topics under investigation. However, there is one major difference. As mentioned previously, earlier studies, largely due to funding arrangements in the United States, tended to be single-investigator (a “series” research system) led endeavours. Nowadays, because of the maturity and complexity of the subject, PBEE research initiatives must, of necessity, be a team approach. Although there is a clear case for ongoing dialogue between researchers and practitioners (and this is happening), there does not appear to be such a clear mission and lines of communication between the academic and design communities and the construction community. The end-user is mostly the design community.

Although considerable research remains to be done before widespread use of PBEE becomes a reality, the long-term success remains in the hands of:

- (i) Code writers: this means both loadings and material codes and the striving for a unity between the two.
- (ii) Engineering Educators: PBEE is a major paradigm shift. It will be necessary to move from the present prescriptive basis of seismic design, to a more informed basis where design is carried out in a framework of how owners will expect their structure to behave in an earthquake. The major challenge will be in conveying such required knowledge, especially to undergraduate students in engineering degree programmes that are already suffering from an overcrowded curriculum.

Another major challenge regarding PBEE is that it does not promise better or more economical structures or systems. The need for buy-in into this new philosophical platform by practitioners may remain unconvincing. It is for this reason at the University of Canterbury researchers are side stepping many PBEE issues and instead attempting to push the envelop that will seek to bring on stream a new generation of structural system that has inherently superior performance characteristics—much of these efforts are centred around design and detailing for damage avoidance.

Another area where PBEE will tend to get tripped up is in making routine design of mundane and ordinary structures a too complex affair. It is considered that the present prescriptive based design process should be retained—albeit in a simplified form where a dependable degree of ‘performance’ can be assured for a reasonable cost. If the owner or designer wishes to have a higher (or lower) level of performance from a certain benchmark, it is only then notions of PBEE should be invoked. This is considered to be of particular importance where the seismic hazard exposure is low. A current example of such an approach is the development of the latest generation of bridge code for AASHTO—a two level design approach has been advocated. A first (default) level of seismic design is the customary prescriptive force-based process (or even a so-called “no-seismic analysis” approach for low to medium seismic zones, that only requires the provision of certain “capacity protection” details). The second and higher level of design requirements is only necessary for important structures or structures in especially hazardous zones such as when near-fault effects or high liquefaction potential become problematic.

## 4 SUMMARY AND DISCUSSION OF RESEARCH TO PRACTICE SUCCESSES (AND FAILURES)

For the abovementioned case studies, the overall success in terms of widespread use can be summarised as follows:

1. *Capacity design*: A complete success story, widespread almost universal use by most leading world codes.
2. *Base isolation*: Partially successful. Not in mainstream use, remains the domain of specialist consultancies. Some codes exist (mostly for bridges but not buildings), but are restrictive,

therefore progress is impeded.

3. *Structural control*: Narrow use, designs are by specialist consultancies. Progress impeded by lack of codes. Many potential solutions have been mooted. These are looking for problems to adopt the solutions. On the other hand, passive control using dampers has been popular in seismic retrofits. For example see Constantinou et al (1998).
4. *SAC*: Successful targeted research to overcome poor rotational capacity of steel connection in pre-1994 (Northridge) construction, good integration of researchers and practitioners.
5. *PRESSS*: In the United States has been successful due to integration of researchers and practitioners. Widespread implementation will be impeded due to present lack of codes and a general dearth of undergraduate education on precast prestressed concrete. In New Zealand, precast construction has leapt ahead of the research community—much catch-up research remains to be done to rectify faulty details.
6. *HAZUS*: Successful program built on widespread use of existing knowledge. Widespread use by planners, but not so much by engineers. Success may be sort lived if the state of the art is not advanced in keeping with the demands of practice.
7. *PBEE*: A work in progress. May not really change how things are built. Key to success will be to have dual-level codes (simplified and advanced) implemented together with undergraduate programmes of education.

It is also of interest to compare the hallmarks of successful programmes from research to practice, and to analyse the principal attributes that lead to a reasonably rapid and successful outcome. Table 1 presents a tabulation showing stakeholder involvement in relation to a programme with respect to its inception until the present time. A grade is given (out a maximum of 5) based on stakeholder involvement. Of particular interest is why a grade may not be 5, and what could be done to increase the grading. Most of these programmes have shown some involvement between the three principal stakeholder communities (research, design and industry), but this is not generally true for codification of ideas to mainstream practice. Also, educational programmes for undergraduates prior to entry to the profession are often lacking.

If funding agencies are serious about getting research into mainstream practice, then part of that continuum is code development as well as course development. Funding agencies argue that neither of these two activities is part of research, and therefore do not merit funding—they contend code and course development should be left to the domain of the profession and universities, respectively.

**Table 1. Some Hallmarks of successes (and failures)**

	<i>Research</i>	<i>Designers</i>	<i>Industry</i>	<i>Codes</i>	<i>Education</i>	<i>Grade</i>
<b>Capacity design</b>	Y	Y	Y	Y	ug + grad	5
<b>Base isolation</b>	Y	some	Y	few	limited grad	3.5
<b>Structural Control</b>	Y	few	Y	few (passive)	very limited grad	3
<b>SAC</b>	Y	Y	Y	Y	not yet, too soon	4+
<b>PRESSS</b>	Y	Y	Y	N	no	3+
<b>HAZUS</b>	N	Y	insurance	n/a	GIS	2+
<b>PBEE</b>	Y	Y	?	emerging	?	2+
+ grade may increase over time, too soon to give final grade						

## 5 CONCLUSIONS

Based on the observations described in this paper, the following conclusions are drawn:

- The “series” model of single investigator research, although leading to lengthy drawn-out programmes, can still play a valuable role. It is often a necessary first step prior to launching a major research initiative.
- The “parallel” research model is evidently the most effective, as it can lead to successful research outcomes in a timely fashion. In the most successful cases from research to practice in earthquake engineering, there is a collaborative engagement between academia (both research and teaching), the design professions (consultancies) and industry (construction, materials and manufacturing).
- There is little evidence that the “Market Forces Model” outlined by Bruneau and Tierney (2002) will be effective for several reasons. First, it appears to be too complex. Moreover, it also appears to be the outcome of heavy handed leading by the US government—pork barrel projects and corporate welfare are hardly a free and open market.
- For new ideas to be mainstreamed into general practice, enhanced undergraduate programmes are needed along with design professionals that can also teach and conduct basic research across the many facets of earthquake engineering.

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