Future directions in seismic design and performance-based engineering

NZSEE 2001
Conference

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ABSTRACT: Based on the present state-of-the-practice in New Zealand, and a world-view of the state-of-the-art, it is argued that in order to make progress towards the building of seismic resilient communities, research and development activities should focus on two fronts: improved design methodologies; and new forms of construction. Performance-based design gives the engineer the ability to inform clients/owners of the expected degree of damage. However, to achieve this it will be necessary to apply displacement-based design methodologies, rather than the current force-based design standards. Society can no longer afford structures that only maintain life-safety; owners and clients demand a higher standard of seismic performance. To improve the post-earthquake performance of structures, it is necessary that new forms of construction be implemented. Examples of two philosophical approaches are given that are referred to as Control and Repairability of Damage (CARD), and Damage Avoidance Design (DAD).

1 INTRODUCTION

As society is prone to serious disruption following strong earthquakes, it is important to assess the effectiveness of earthquake engineering mitigation measures and the management of seismic risk. This requires that a perspective be drawn from past and present practice in order to build a sense of where the future direction of the art and science of earthquake engineering should be guiding the profession. This paper discusses some of the central themes of earthquake/structural engineering in terms of the past, present and future, and attempts to give some insight into the future of seismic design and how it relates to the broad spectrum of performance-based engineering.

2 EARTHQUAKE ENGINEERING IN THE PAST

Prior to the 1970s, few structures were earthquake engineered. Although engineers realised as far back as the early 1900s that earthquakes were capable of inflicting considerable damage to constructed facilities, only important structures considered limited facets of earthquake engineering. The emphasis in the early days of formalised earthquake resistant design revolved around prescriptive code lateral loads. The prescribed level of lateral loading was minimal; well below the levels necessary to obtain elastic behaviour. Code writers made this conscious choice based on the empirical evidence that weaker structures were still able to survive earthquakes. The fundamentals of earthquake engineering, in terms of structure dynamics and particularly non-linear behaviour, were neither well understood nor widely implemented prior to the 1970s.

Perhaps the watershed event in earthquake engineering was the 1971 San Fernando earthquake. That earthquake was not particularly strong and yet many so-called seismically designed structures suffered significant damage and collapse. Several bridge structures that were under construction collapsed and this immediately brought into question their design philosophy. Engineers soon realised that there was an interrelationship between structural strength (the applied design loads) and the structural ductility (structural detailing). Following this catastrophic event, considerable investment was made in the United States in investigating improved methods of seismic design. Those early research efforts were mostly focused on advancing elastic structural dynamic analysis. A better understanding of elastic seismic response does not really give the designer a better insight into inelastic behaviour. This is because the provided strength of members based on reduced elastic forces is somewhat random, so the behaviour of critical elements is a matter of chance.

Interestingly, many of the major breakthroughs in earthquake resistant design came with the pragmatic efforts of New Zealand structural engineers who understood the interrelationships between strength, ductility and failure mechanisms. It was New Zealand engineers in the 1970's who spearheaded developments in ductile detailing of structural elements with a particular emphasis on *capacity design.* Capacity design is a means of obtaining predictable behaviour based on a known heirachy of failure mechanisms. Since the 1970's this has often been referred to as the "strong column-weak beam" approach.

It should be emphasised that the earthquake resistant design of structures in New Zealand, the United States and elsewhere has historically been based on a philosophy of design for ductility where damage is expected, but life-safety is maintained. With the use of "Importance Factors", critical and/or important structures are designed to be marginally stronger, but still not elastic. Because the degree of inelasticity is not strictly defined, the level of damage in a strong earthquake is unknown, but presumably less than an ordinary structure.

Evidently design engineers in New Zealand in the 1970's were uncomfortable with this unknown degree of damage. As a result New Zealand engineers again led the way to another revolutionary breakthrough with the use of seismic isolation. With seismic isolation, the intent is for the superstructure to remain elastic and damage-free, with the majority of the seismic energy and induced displacements being handled with special isolation bearings and/or mechanical energy dissipating devices.

3 EARTHQUAKE ENGINEERING IN THE PRESENT

Since the 1970s, the science and art of earthquake engineering has been maturing rather than revolutionised. New Zealand engineers have continued to be innovative, particularly with the use of precast concrete structures. Little progress has been made, however, in terms of design methodologies. Designs continue to be based on reduced elastic forces (force-based design) along with the use of prescriptive detailing of members and connections. This design approach leads to implied levels of ductile behaviour, but design engineers are unable to give their clients any assurances as to the degree of damage sustained by a design level earthquake. Other than providing a minimal level of strength, designers have little control over expected performance outcomes of their designs. Perhaps the only choice a designer has is to use a form of construction such as seismic isolation if the client requires a structure to be essentially damage free after an earthquake. However, seismic isolation is certainly no panacea, indeed, for high-rise construction is generally unsuitable in its present form. One might conclude that the present state-of-practice of earthquake engineering is pretty much in the doldrums.

Although progress in advancing the present state-of-practice in earthquake engineering is seemingly stalled, much exciting research activity has been conducted in recent years to advance the state-of-the-art. Improvements in earthquake resistant design methodologies, as well as new approaches in the construction of structural systems, have been based on a considerable body of research conducted in the United States. Recent moderate-level earthquakes that sustained considerable damage to structures, that were thought to be well engineered from a seismic point of view, have spurred on this work. Recent earthquakes such as 1989 Loma Prieta, 1994 Northridge and 1995 Kobe occurred near large metropolitan areas. Few well-engineered structures collapsed or led to fatalities, but many structures sustained a considerable degree of damage that was considered to be unacceptable by their owners, as well as the community at large. It is for this reason that there is presently a major movement towards performance-based engineering.

Whereas in the past structures were designed for life-safety, many communities now require certain structures, particularly those that are part of a critical system such as schools, hospitals and bridges, to be functional following a strong earthquake. Moreover, sophisticated corporate clients now demand more from the engineer. This is particularly so where an industry is based on just-in-time inventory management such as in the computer and automotive industries. Therefore to provide a measure of post-earthquake serviceability, it is necessary to move away from the force-based design methods of the past. Earthquake engineers now need a special form of performance-based engineering to satisfy their clients and society demands.

In order for the earthquake engineering profession to provide society with a seismic resilient community, it will be necessary to advance the state-of-the-art (and subsequently practice) in two areas: design methodologies and construction practices. These two facets of earthquake engineering will be discussed in what follows.

4 EARTHQUAKE ENGINEERING IN THE FUTURE: DESIGN METHODOLOGIES

To enable the designer to provide clients with a sense of the outcome of an earthquake on a structural system, it is necessary to either abandon or at least supplement traditional force-based design methods. Although the force-based capacity design approach is able to assure life-safety, it is unable to provide the designer with any insight as to the expected degree of damage that will be sustained in various parts of the structure. A displacement-based design shows promise as a means of identifying increasing levels of damage up until the point of structural collapse. This enables the engineer to design a structure in accordance with the client's wishes. In other words, the engineer is now able to manage the seismic risk by balancing the results of the expected outcome (in terms of damage) with the cost of providing the structure.

Although displacement-based design shows much promise and elements of this are now being used in certain contemporary codes, little has been done on establishing a full performance-based design approach for complex structures such as multi-storey buildings and large bridge structures. Research still needs to be conducted on the full generalisation of displacement–based design approach. This is particularly necessary for structures that may be irregular (structures with torsion or strength eccentricities), structures with significant higher mode effects (tall buildings and long bridges), and structures with a mixture of materials and elements in their construction.

In the United States, efforts are well underway to implement performance-based engineering both for the seismic design of new and the seismic retrofit of existing structures. An example is given below which is an adaptation of proposed seismic design and retrofit measures for highway bridge structures.

In broad terms, the performance-based design objectives for bridges are two. First, bridges should ideally perform in a "mostly-elastic" fashion when subjected to earthquakes with a high-probability of occurrence (return period of 100 years, or 50% exceedance probability in 75 years). Secondly, for low-probability earthquakes (return period of 2500 years, or 3% exceedance probability in 75 years for new structures; lower levels may be permitted for existing structures) and depending on the desired performance level, bridges should ideally dissipate energy through inelastic deformation in earthquake resisting elements. Depending of the type of analysis, the demand and capacity may be expressed in terms of forces (bending moments in the plastic hinge zones or shear forces in isolation bearings) and/or displacements of the structure at the centre of mass.

For seismic design and vulnerability analysis the choice of the mathematical model and analysis procedure is based on the requirements of which defines the *Seismic Design and Analysis Procedure* (SDAP) for structures or the *Seismic Vulnerability and Analysis Procedure* (SVAP) to be used for new existing structures. Different design methods are used depending on the level of seismic hazard and expected seismic performance, as shown in Table 1. Note here the seismic hazard is principally related to the 1.0 second spectral acceleration amplitude which is the product of $F_v S_1$ where F_v is the soil type factor and S_1 is the 1.0 second amplitude for a stiff soil/soft rock site.

Seismic Design and Seismic Vulnerability and Analysis Procedures (SDAP/SDAV) use analysis methods of an increasing degree of sophistication and complexity depending on the performance expectation and seismic hazard. The performance expectation is related to the damage expected following an earthquake.

Table 1 Seismic Hazard Levels and Methods of Seismic Design and Analysis

Seismic Hazard Level	Spectral Acceleration at period T=1 sec.	Seismic Design or Vulnerability and Analysis Procedure (SDAP/SVAP)	
		Life Safety Performance	Operational Performance
I	$F_vS_1 \leq 0.15$	A	A
II	$0.15 < F_vS_1 \leq 0.25$	A/B	C/D/E
III	$0.25 < F_vS_1 \leq 0.40$	B/C/D/E	C/D/E
IV	$F_vS_1 > 0.40$	C/D/E	C/D/E

Table 2 presents the relationship between the performance expectation and damage states. To encompass a broad range of seismic performance, five levels are shown in Table 2 in terms of general post-earthquake structural performance outcomes. In Table 2 column (1) lists the five damage states *(DS1, DS2, ... DS5)*; column (2) gives the two principal performance levels for design and retrofitting purposes; column (3) presents broad descriptors of damage that are sometimes used as indications of the overall post-earthquake "state-of-health" of the structure; column (4) gives a descriptor of seismic damage in terms of post-earthquake repair needs and utility; column (5) explains the nature of repairs for a given damage outcome; and column (6) gives and indicative period of time the structure may be out of commission as a result of earthquake-induced damage.

Table 2. Seismic performance for various damage states.

Damage State	*Performance expectation*	*Descriptor for degree of damage*	*Post-earthquake Utility of structure*	*Repairs required*	*Time of Outage expected*
1	Operational	None (pre-yield)	Normal	None	--
2		Minor/slight	Slight damage	Inspect, adjust, patch	<3days
3		Moderate	Repairable damage	Repair components	<3 weeks
4	Life-safety	Extensive	Irreparable damage	Rebuild components	<3 months
5		Complete	Collapse	Rebuild structure	>3 months

Seismic Design/Vulnerability and Analysis Procedures (listed as methods A to E in table 1) use the following seismic demand analysis and/or seismic Displacement Capacity Evaluation procedures. These are given in order of increasingly higher-level of ability to represent structural behaviour. A higher level analysis may be used in place of a lower-level analysis.

4.1 *SDAP A and SVAP A: Connection Force Checks*

This is where a prescriptive level of resistance is required for bearing seats. The intrinsic strength of the structure based on other (gravity/wind) loading conditions is considered to be satisfactory for resisting earthquakes.

4.2 *SDAP B and SVAP B: No analysis*

This is where the relative strength of the members and the adequacy of certain key details are checked. Further analysis of the displacement demands need not be checked. Ductile detailing and capacity protection of elements is provided based on initial requirements for gravity loads alone.

4.3 *SDAP C and SVAP C: Capacity Spectrum Analysis*

The seismic response of a regular structure is modeled as a single degree-of-freedom system, and the demand analysis and capacity evaluation is combined in a single procedure. (This type of analysis has commonly been used for the design of seismically isolated bridges). This method of design/analysis can be either approached from a force-based or displacement-based perspective. However, it is mostly intended to be a displacement-based approach. One very attractive attribute of this method is the engineer need not know the natural period of vibration—it is implicit in the analytical formulation.

4.4 *SDAP D and SVAP C: Elastic Response Spectrum Analysis*

Seismic demands are determined by either the uniform load method or multi-mode response spectrum analysis. For bridges with a regular configuration, the uniform load method may be used, otherwise a multi-mode dynamic analysis is required. This is essentially a traditional force-based method of design based on the widely used R-factor approach. Adjustments are made to R-factors for short-period structures.

4.5 *SDAP E and SVAP E: Two Level Design*

This is a the highest level of seismic design and analysis sophistication. The structure is designed for elastic conditions and frequent return period earthquakes (for example, 100 year return period). A multi-modal response spectrum analysis is then conducted and the displacement capacity for the maximum considered earthquake (MCE which has a return period of 2500 years) is then assessed. A non-linear static displacement capacity evaluation is then conducted. This is commonly referred to as a “pushover analysis.” The displacement capacity of independent piers, bents and frames is determined from the nonlinear behavior of the inelastic components. For the MCE event, the damage-state checked for regular structures at the life-safety performance expectation (damage state 4). For “Important” or “Critical” structures that are required to be operational following an earthquake, a lessor standard of damage is required as respectively given by either damage states 2 or 1 in Table 2.

5 EARTHQUAKE ENGINEERING IN THE FUTURE: CONSTRUCTION PRACTICE

The most common method of construction in New Zealand and other western countries are cast in situ reinforced concrete and masonry structures. Steel structures are also common for light commercial and industrial construction, but this class of construction is not normally highly vulnerable to earthquakes. Much of the development over the last three decades in earthquake engineering has revolved around improving the seismic resistance of concrete structures and using, to a lesser extent, masonry structures. Both of these forms of construction are popular because the materials are durable, almost maintenance free, and relatively inexpensive. However, in western countries the cost effectiveness of concrete and masonry structures is being constantly eroded due to high on-site labour costs of construction. It is for this reason that in the last decade, there has been a marked increase in pre-cast concrete construction. Higher quality materials can be manufactured in factory-like conditions.

In New Zealand, the earthquake engineering profession has reacted to this need for increase use of pre-cast concrete structures by conceiving forms of construction that mimic the behaviour of their cast in situ concrete counterparts. Although this approach has been effective from a standpoint of seismic resistance, it is not necessarily the most cost effective. It is for this reason that in the United States, the National Science Foundation has supported the PRESSS research program with the objective of developing modular pre-cast systems that do not necessarily mimic cast in situ counterparts.

The recently completed PRESSS (pre-cast seismic structural systems) program has matured to the point that seismic resistant structures using hybrid connections can now be constructed on a routine basis. See for example Priestley et al. (1999). It can be expected that the construction of such systems will see their way into New Zealand practice in the foreseeable future. In spite of the considerable promise shown by the use of hybrid pre-cast concrete systems as a outgrowth of the PRESSS research program, there are still a number of key concerns that confront New Zealand designers before widespread application is likely to take place. It is evident that the new class of hybrid pre-cast concrete buildings can be easily implemented for regular structures. It is yet unknown as to their ease of implementation for the majority of structures built that can be classified as irregular.

One of the attractive features of PRESSS-type buildings is that they are able to provide the owner a high level of performance in an earthquake. That is, for moderate level earthquakes the degree of damage is likely to be reasonably superficial. In spite of this, it should be emphasized that PRESSS buildings are not damage-free. Moreover, under very large earthquakes, some damage to PRESSS buildings is to be expected, particularly in the connection regions, and it is questionable whether such damage is repairable.

It is considered that one of the major research needs for New Zealand practice is the development of new structural systems that subscribe to the notion of performance-based design. In particular, it is desirable that structures should have a measure of post-earthquake serviceability. If this is to be the case, then following a strong earthquake it is necessary that damaged structures should be repaired, or better still, that the structure be damage-free. Needless to say, owners and developers would prefer to meet these objectives without an increase in construction costs.

Some effort has already taken place in this direction in the United States for bridge structures. High levels of seismic performance are particularly desirable for bridges as it is the public's expectation that busy highway systems are kept operational at all times. There are two approaches for providing this high level of damage referred to as CARD and DAD.

5.1 *Control And Repairability of Damage (CARD)*

This is a type of construction that uses repairable parts in plastic hinge zones to permit the damaged concrete and steel to be removed and replaced after a strong earthquake. Instead of using regular longitudinal reinforcing bars, prestressing threadbars are used in the plastic hinge zones. These prestressing threadbars are machined down to about 70 percent of their original diameter. This ensures that the ultimate tensile capacity on the reduced area of the bar is less than the yield strength on the route thread diameter outside the hinge zone. These so-called fuse-bars are connected via couplers to the surrounding column and beam column joints. It is a fairly straightforward matter to remove damaged concrete, hoops, and bars and replacing these parts to have full restoration of the structure. For further details, refer to Cheng and Mander (1997), Mander and Cheng (1999) and Dutta et al. (1999).

Another advantage of the CARD system is that it can be constructed from pre-cast concrete elements. For bridge systems, this is particularly desirable as it minimises construction time at the bridge's site. In essence, the CARD system mimics traditional construction that has been designed for ductility.

Although this system shows promise in that it permits post-earthquake restoration, perhaps the major disadvantage is that some concrete work still has to be done at the site—both during construction and after an earthquake. An enhanced system is described in following subsection.

Another interesting application of the emerging Control and Repairability of Damage philosophy is a novel application to steel structures. This development by Ricles et al. (2001) was motivated by the very poor performance of steel moment resisting frames with welded connections in the 1994 Northridge earthquake. Ricles et al propose that the traditional welded moment connections be replaced by a new type of rigid connection. The connection starts with a common top-and-seat angle (semi-rigid) connection detail, and then has concentric prestress applied to the beam through the entire beam-column joint. During an earthquake, on reversed cyclic loading the top and seat angles yield and dissipate energy, but the prestress closes the connection and the structure is re-centred. None of the main structural elements are damaged, as the connection strength is limited to about 70 percent of the plastic capacity of the girders. Damage is limited to the top and seat angles. These can be replaced, if necessary, but this would only be necessary after an extremely strong earthquake event where the fatigue-life of the connection was substantially consumed. This form of construction also has the advantage of not requiring any form of on-site welding.

5.2 *Damage Avoidance Design (DAD)*

This is a fully modular pre-cast concrete system that has “dry joints.” All the principal structural elements can be factory-cast and then assembled on site. The structural elements are tied together through post-tensioning. The post-tensioning provides rigid moment connections at beam-to-column or column-to-beam connections. If the interfaces between the connections are constructed from strong materials such as steel, then during an earthquake the members tend to rock, steel against steel, and no damage is done to the pre-cast concrete elements. This system has been tested on the laboratory strong floor with near full-sized elements as described in Mander and Cheng (1997). A one-quarter scale bridge model has also been tested on the shaking table by Mander et al. (1998).

One of the fascinating aspects of this class of construction is that the rocking connections dissipate kinetic energy into the elastic half-space. It is not known how well this class of system will work for more complex multi-degree of freedom structural systems such as multi-story buildings. Clearly this is an area where further research is required.

Nowadays, one of the major concerns of society is the need for sustainable development. It would be interesting to develop building systems from an assembly of individual parts that require no site-cast concrete (this also means no topping slabs for floor systems). If the building could be held together fully with purpose built connections and/or post-tensioning, then when the structure is no longer needed, it could be dismantled and reused in a similar or different form elsewhere. The emerging DAD approach is moving in this direction, but considerable research and development work remains to be done.

5.3 *Passive Energy Dissipation*

It is realised that the new methods of construction described above will not necessarily appeal to all owners and/or design engineers. Thus, it is desirable that existing forms of construction such as structures with limited ductility have their post-earthquake performance attributes enhanced. One way of doing this is to provide a passive control bracing system to the structure. New Zealand has already seen examples of this class of construction with Union House in Auckland and the Central Police Station in Wellington. However, there are new methods of providing passive control that are somewhat different to the lead-extrusion damper system placed at ground level. There is a considerable body of research that now exists that has been motivated by the need to seismically retrofit existing structures that possess limited or no ductility. This generally entails some form of passive bracing system where the braces consist of either viscous dampers or visco-elastic spring dampers. There have been a significant number of existing buildings that have been retrofitted in the Untied States and Canada using these methods. There have also been several new structures that have been constructed with these damper devices. For a general treatise on this subject see Soong and Dargush (1997). Also, there are several novel applications such as the toggle-brace-damper seismic energy dissipation system proposed by Constantinou et al. (2001), and a supplemental load balancing system that uses a combination of tendons, dampers and fuses proposed by Pekcan et al. (2000). These latter two examples show considerable promise for the retrofit of existing non-ductile structures, as well as the primary energy dissipation system in new structures that are constructed using either moment frames and/or walls. With such systems an improved standard of post-earthquake performance can be assured.

In the foreseeable future it is considered likely that New Zealand engineers will be attracted to using innovative damping systems for the seismic retrofit of existing structures, as well as the primary means of minimising damage in a class of new structural systems. To enable progress to this point, it will be necessary to continue the conduct of research in this area, as well as the need for developing user-friendly design codes.

6 CONCLUSION

This paper has reviewed from an historical perspective past and current developments in earthquake engineered structures. Based on the present state-of-the-practice in New Zealand, and a world-view of the state-of-the-art, it is argued that in order to make progress towards the building of seismic resilient communities, research and development activities should focus on two fronts: improved design methodologies and new forms of construction.

Performance-based design gives the engineer the ability to inform clients/owners of the expected degree of damage to enable a better management of seismic risk. To achieve expected performance outcomes it will be necessary to either abandon, or at least supplement, current force-based design standards with displacement-based design methodologies.

Improved design methodologies alone will not lead to a significantly superior level of seismic resilient communities, but rather lead to a superior standard of performance-based engineered structures where the post-earthquake outcome will be known with a certain degree of confidence. Moreover, modern society can no longer afford structures that only maintain life-safety—especially owners of transportation systems and principal manufacturing industries, who demand a higher standard of structural performance. Ironically, owners do not wish to pay more for a superior standard of seismic performance. Therefore, to improve the post-earthquake performance of structures, it will be necessary to develop new forms of construction, which are at least repairable or preferably damage-free. To this end, this paper has given two philosophical approaches that are referred to as Control and Repairability of Damage (CARD), and Damage Avoidance Design (DAD).

Existing forms of construction may continue to be used. This includes regular ductile structures, as well as structures with a limited ductility capability. However, it is contended that in order to improve the post-earthquake utility of this traditional class of construction, a supplemental passive control system should be included as part of the earthquake resistant design.

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