Potential seismic resistant design strategies from other fields

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2005 NZSEE Conference

ABSTRACT: This paper presents an investigation into potentially new seismic design strategies for buildings, derived from areas outside the customary scope of earthquake engineering. The research examines fields such as car design, molecular behaviour and animal structure. Six concepts were developed into systems that may be constructible. These are titled: Plate Springs, Inertia Valves, Tension Tendons, Structural Laminates, Structural Kinks and Complex Links.

A summary of the proposed ideas in terms of anticipated seismic design attributes is presented as well as an evaluation of their originality, architectural value and future potential. At this stage, each of these proposals is only speculative. Their value lies in their existence as possibilities for future exploration, an indication perhaps of the future of seismic design.

1 INTRODUCTION

This paper grew out of a desire to understand the state of seismic design today – what people are developing and why, as well as what is currently in use in the field: important information in the context of practicing architecture in New Zealand.

Instead of just researching and cataloguing current techniques, a much more appealing and (hopefully) enlightening process suggested itself. By generating ‘new’ ideas, the underlying concepts behind seismic design could be clarified, as well as considered from a fresh perspective. This research was also a rare opportunity to speculate - without the reality check of quantity surveyors.

The search for ‘transferable concepts’, was inspired by the successful adaptation of hydraulic dampers to buildings, and the potential of naturally-occurring mechanisms to develop into an important research area. This impulse to speculate wholesale on new seismic design systems has occurred previously and successfully. In 1976, Dr. Ivan Skinner and his team developed a series of energy dissipating concepts for use in seismic design. The set of five mechanisms were published in 1980; the use of elastomeric isolation bearings being a conceptual breakthrough in structural thinking.

The research process involved choosing fields for study based on the likelihood of their containing transferable systems. As well as directly useable components, valuable principles might also be adapted into construction methods.

While it is perhaps obvious to expect industrial technology to have developed mechanisms for controlling and modifying dynamic forces, nature is also faced with situations similar to those confronting engineers, such as wind loads and stresses related to locomotion. Nature often solves these problems in ways that are both high performance and inherently environmentally friendly. As a result, the following proposals range from simple reconfigurations of existing technology to ideas that bear little resemblance to their original sources of inspiration.

2 CONCEPTS

How does one go about finding ‘transferable concepts’ amongst the limitless expanse of existing dynamic systems? The search for mechanisms that could respond to the displacements and accelerations, as well as the frequency and duration of seismic activity, quickly became a rambling troll through technical tomes and magazines. The following six ideas each sprang from an initial published image, and include the concepts considered to be the most easily adaptable.

2.1 Plate Springs

Motor vehicle design is a logical field for investigation as it deals with a huge variety of applied and generated forces, the control of which requires exact but also robust technology. The image of a diaphragm spring captured my attention (Fig. 1). It was an elegant solution for a clutch plate system, the inherent properties of the shape perfectly suiting the performance requirements.

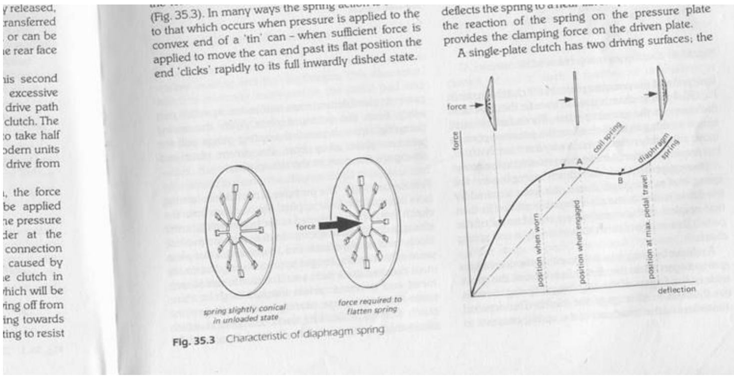


Figure 1 Displacement dependant behaviour of plate spring (Hillier 1990)

The idea of a spring that changed its properties depending on the level of force it was subjected to brought forth visions of an isolation system that would respond only under designed loadings. It seems to offer the possibility of remaining stiff under moderate loads and ‘switching on’ under extreme conditions. This could make available a degree of isolation only at forces over a certain level, allowing the building to displace up to distances equal to the spring’s maximum deflection. The resumption of stiffness at this point could provide a natural limit to the building’s displacement.

Research into similar spring forms and applications uncovered the cone shaped ‘Belleville Washer’, a disk spring that applies clamping pressure in bolted connections undergoing repeated loading cycles. The simple spring design can be elaborated to attain a variety of force v. deflection behaviours.

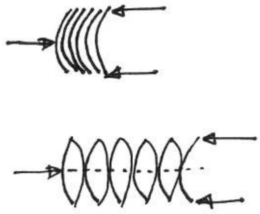


Figure 2 Plate spring combinations: one stacking arrangement increases stiffness while another increases the maximum displacement

Because the spring itself remains elastic it does not dissipate energy - except in small amounts through friction. This means any seismic application would need to incorporate a damping element. Morishita (2004) tested a similar system using disc springs for vertical isolation, but did not make use of the spring’s ability to invert. Engineers have also discovered a way of making a monostable plate spring where, even when fully inverted, the spring will snap back to its original position. Possible issues with the system include: size – what happens when you scale it up to building size; earthquake energy variability – is the system too specific to be useful; how does the spring perform under non-axial loading?

2.2 **Inertia Valves**

Conventional shock absorbers are all speed sensitive - the faster the shock absorber is extended or compressed, the more resistance the piston passing through the fluid encounters. This means that under small accelerations the damper provides little resistance to displacement. The ability of a damper containing an inertia valve to discriminate between levels of acceleration is very interesting, allowing the element to remain stiff until the design accelerations are reached.

These mountain bike shocks have been designed to be ‘active’ in one direction only, absorbing the abrupt jolts from travelling over rough ground but not the pedaller’s energy. The mechanism operates through an inertia valve; only when the accelerations are high enough can the fluid damper come into action.

Figure 3 An inertia valve-controlled damper developed for mountain bikes (Fox Brain Shock 2003)

When the damper is shifted fast enough, the inertia of its metal sleeve overcomes the resistance of a spring, uncovering the orifice in the piston head. The element can then function like a normal damper until the speed of the piston head drops and the damper becomes stiff. As it is mechanical and works in direct response to the laws of physics, it responds more quickly than an electronically controlled shock absorber dependent on a computer directing a small motor to open the valve.

As designed for mountain biking, the shock absorber operates under acceleration from one direction only. This is perhaps a less important feature when considering the action of buildings in earthquakes. The placement and orientation of an inertia valve could be configured to take account of movement in both directions.

Experimental testing would show if the valve creates a damper that behaves in a way useful to seismic design. A possible issue could be that the quick reversals of direction characteristic of seismic ground motion cancel out the relative shift of the mass due to inertia. The simplicity of the system’s direct response to variances in acceleration is worth further investigation.

Such an ‘intelligent’ passive device may respond like an actively-controlled damper. Seismic energy is dissipated as the fluid is forced through a small orifice. Displacements are limited by damper size only. While this is a simple idea that modifies existing technology, calibration for specific structures may require extensive analysis. Maintenance requirements and methods of use are the same as for conventional hydraulic dampers, so the damper could be used in many of the ways existing fluid dampers are used now.

2.3 **Tension Tendons**

One of the mechanisms that animals have developed for reducing damage from high impact forces relies upon the elastic properties of their tendons. The configuration of bones and joints causes the tendons to stretch when the foot makes contact with the ground (Fig. 4). The force of impact is stored elastically and released to give the animal spring.

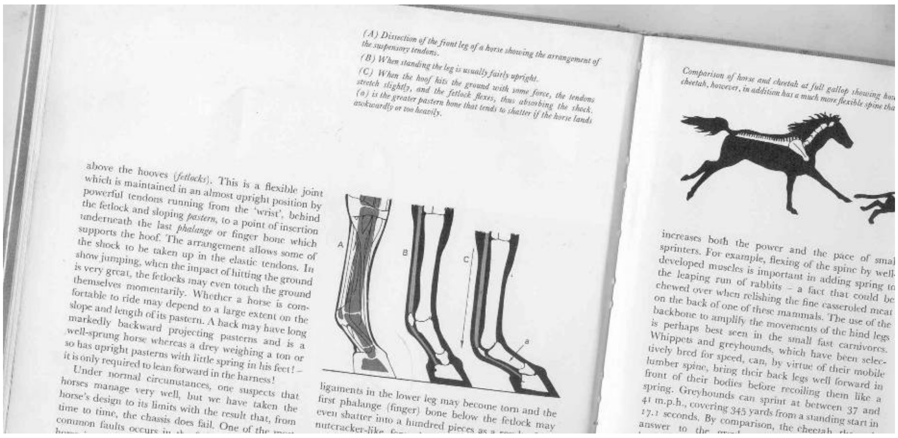


Figure 4 Elastic behaviour of horse leg tendon to reduce impact shock (Sparks 1972)

Tension elements for resisting lateral loads form part of many structural systems, such as concentric bracing, but there does not seem to be anything that uses tension and elastic deformation as efficiently as an animal. This may be due to scale and material properties, but there is also a difference in configuration. The animal mechanism takes advantage of the tendon's response to non-axial loads, the angle increasing the efficiency with which the tendon can straighten the joint when vertical loads are removed.

Extrapolating the idea into construction revealed another interesting characteristic. If a continuous 'tendon' is passed through connections (that allow it to stretch as a whole) between two objects, under irregular displacement the tendon will develop tension evenly along its length, and exert tension equally on all connections. This could make it possible to reduce the load capacity of all the elements without compromising performance. A tendon developed for a building would most likely be a steel cable. Although a 'bungy-style' rubber cable would offer greater elasticity, steel has the advantage of remaining strong even after plastic elongation. The cable and connections could also be configured to induce tension under displacements in either direction (Fig. 5).

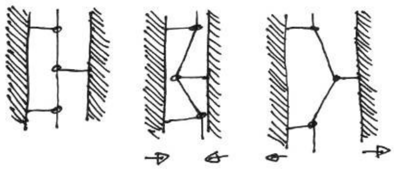


Figure 5 Displacements perpendicular to the cable in either direction place the cable in tension

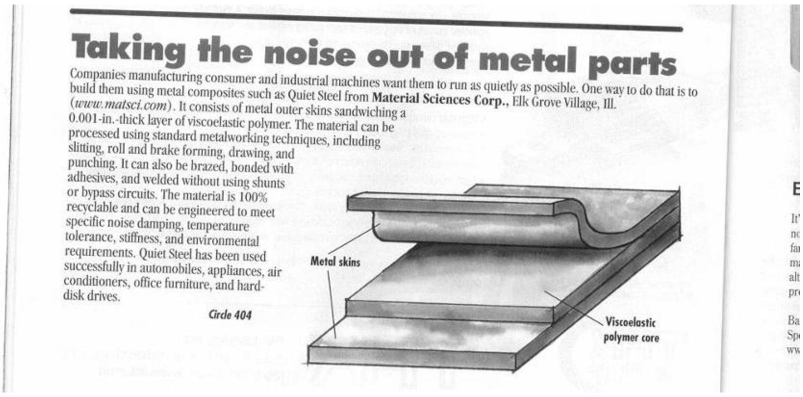
The system offers the possibility of reducing the relative movement between buildings by transferring the seismic energy to the cable. This energy then gets released equally back to each building as a restorative force, assisting the buildings in returning to their original positions.

Experimental studies are being conducted into damping between buildings (Cimellaro 2004), but these 'tendons' offer a way of utilising the stored elastic energy positively. Another potentially useful aspect is the ease with which cables can be manufactured, as well as replaced after any significant earthquake. A seismic system based on cables could possibly be easily adapted to any existing building arrangement that has suitable spaces. As an exterior system, interstitial tendons could have a significant visual impact on the fabric of a city.

2.4 **Structural Laminates**

Laminated systems have been developed in many fields to reduce the transferral and propagation of vibrations. In laminated glass, the 1.5 mm resin interlayer reduces the effect of the glass resonating at certain frequencies and becoming 'transparent' to particular sounds.

In 'Quiet Steel' (Fig. 5), the visco-elastic layer provides the sheet with a degree of vibration damping, without reducing its usability. Damped structural connections using visco-elastic layers are already in use, but by extending the idea of laminates into the body of a building, the basic structure is imbued with a greater degree of damping.


Taking the noise out of metal parts

Companies manufacturing consumer and industrial machines want them to run as quietly as possible. One way to do that is to build them using metal composites such as Quiet Steel from **Material Sciences Corp.**, Elk Grove Village, Ill. (*www.matsci.com*). It consists of metal outer skins sandwiching a 0.001-in.-thick layer of viscoelastic polymer. The material can be processed using standard metalworking techniques, including slitting, roll and brake forming, drawing, and punching. It can also be brazed, bonded with adhesives, and welded without using shunts or bypass circuits. The material is 100% recyclable and can be engineered to meet specific noise damping, temperature tolerance, stiffness, and environmental requirements. Quiet Steel has been used successfully in automobiles, appliances, air conditioners, office furniture, and hard-disk drives.

Circle 404

Figure 6 Laminated steel panels reduce vibrations in automobiles, air conditioners and disk drives (Quiet Steel 2003)

A visco-elastic layer would dissipate seismic energy through hysteresis, even though the structure remains elastic. Activated by small displacements, the laminated layer could respond to all dynamic loads that the host member is subjected to.

Composite steel sections that incorporate visco-elastic layers could be produced. Shear walls are also a candidate for lamination, especially concrete panels. Existing precast technology already inserts layers of materials such as polystyrene. It may be possible to create laminates post-construction by pouring a liquid polymer or resin between wall layers that then sets later. This could be an option for existing concrete masonry walls.

Future investigation would need to determine if the structural laminates behave as anticipated, and whether the polymer layer has any detrimental effects. Possible issues include: the laminated structure's response to fire, especially in terms of losing strength or releasing toxins; the cost of producing a 'laminated' building in comparison to a normal structure with conventional damping components; and under what conditions would the element de-laminate?

2.5 **Structural Kinks**

This idea grew out of an exploration of sacrificial zones in automobiles. These are areas in a car structure that are designed to absorb energy in a damaging collision. This is similar to the principle behind Capacity Design, in that it is an attempt to dictate how and where the structure will fail in order to minimise injury or fatality. Closer inspection of the energy-absorbing frame (Fig. 7) reveals the mechanism by which the frame dissipates energy. The steel frame is kinked where it is supposed to crush on impact. Bending moments form at the kink under compression, inducing yielding in the steel.

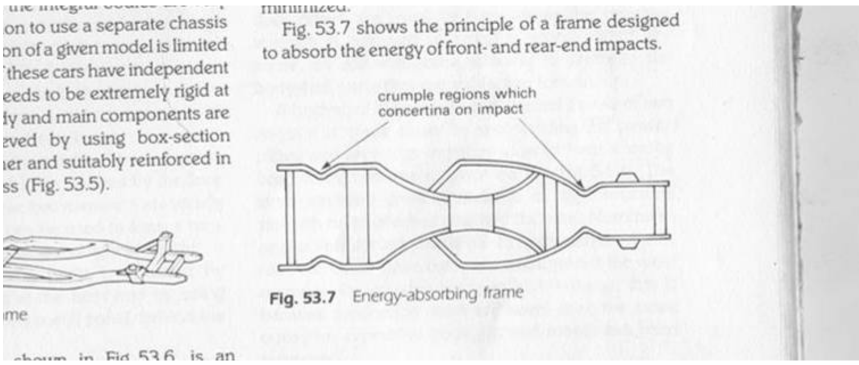


Figure 7 An energy-absorbing frame used in car construction (Hillier 1990)

The concept of the kink is something that could be easily transferred to seismic design. If adapted to bracing design, a simple bent steel brace could dissipate seismic energy. Under expected wind loads the brace would remain stiff, but under large lateral loads, compression or tension in the kinked brace would cause it to yield.

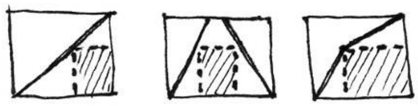


Figure 8 Comparative brace configuration

A kinked brace may perform similarly to an eccentrically-braced frame in terms of energy dissipation, but offers many architectural possibilities. Aside from its distinctive form, a kinked brace allows a much greater proportion of useable space underneath, compared to conventional braces.

Other possibilities for kinked structure include columns that undergo tension and compression due to overturning moments, or beams resisting lateral loads. The aesthetic of a 'kinked architecture' could have a strong visual (and identifiably seismically related) presence in the built environment.

2.6 **Complex Links**

Thinking about the forces that trees are subjected to, and watching how they moved in response, provided an insight into how they resist wind loads. Each branch and twig of a tree is of a different thickness and length. Each of these limbs therefore has a different fundamental period of vibration. After an initial gust, the movement of branches rapidly falls out of phase, reducing the total movement (and associated base shear) experienced by the tree trunk.

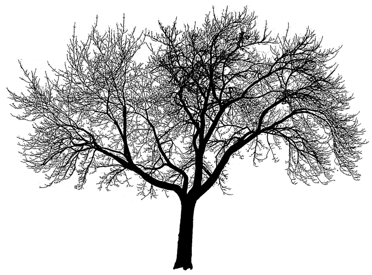


Figure 9 Trees exhibit highly complex structures

Applying this concept to buildings offers some interesting possibilities that could take advantage of the mass of individual building sections. The inertial force of a mass damper provides a similar out-of-phase resisting force, but is generally used as a single or paired addition to a structure.

To achieve a tree-like response from a building would require a number of independently-moving sections, connected with isolating and damping components. The height, mass and stiffness of each section would need to be varied enough to result in diverse fundamental periods. Although the complex motions of the building sections in a real earthquake would require extensive computer analysis to predict, such testing may establish whether any detrimental harmonic action might occur. Experimental studies have been made of two different-sized linked structures that show promising results in terms of damping efficiency (Peng, Yan & Zhou 2004).

The structural separations could be (and probably would have to be) made apparent in the complex massing of the exterior form of the building. The full realisation of this idea could only be accomplished in a new building, but a similar utilisation of uncoordinated movement might be possible in existing city blocks.

Possible issues for future exploration: is there an optimal number of and configuration of building sections that provide the most effective damping; what are the implications for other building systems such as service connections, weatherproofing systems, cladding components and fire design?

3 SUMMARY

The concepts presented here are experimentally untested and their viability remains theoretical. Evaluation therefore can only be a subjective analysis of the assumed performance and degree of potential present in each idea.

Table 1 assesses each concept in terms of originality, architectural expression and future potential.

Table 1. Summary of proposed concepts.

Idea	Originality	Architectural Expression	Potential	Field
Plate Springs	Experimental testing has been conducted on a related system using disc springs for vertical isolation of machinery in nuclear facilities. This utilises elastic spring characteristics, but not its snap action.	It is unlikely that systems using disc springs would appear much different, or be more visible, than existing fluid dampers. They also would not require an unconventional structural configuration.	The adjustability of the spring design to produce a wide range of performance modes is worth further investigation.	Automobiles
Inertia Valves	Although fluid dampers are in use in many buildings in the USA, the inertia valve has not yet been incorporated into a seismic resisting system.	This would be a small change to damper technology with few architectural implications.	The responsive ‘active’ behaviour of the mechanism that does not require computer control is valuable.	Mountain Bicycles
Tension Tendons	There is no structural mechanism currently in production that is similar to this.	A highly visible element with possibilities for interesting articulation.	Computer analysis and experimental testing are required to establish the viability of this system.	Animals
Structural Laminates	Although visco-elastic layers have been used in steel connections, no example of use across an entire building structure can be found.	As a very thin interior layer, this technique would not be visually apparent, but the concept of structure as layers with different attributes could be explored architecturally.	Although perhaps technically difficult to develop, a successful system could be easily mass-produced.	Industrial materials
Structural Kinks	This idea has not been consciously applied to seismic structural design before.	A strong visual form that could have a big impact on seismic architecture. The idea also has benefits for planning and enhancing of useable space.	A very easily realisable concept that is potentially very significant.	Automobiles
Complex Links	Damping between pairs of buildings is currently being studied, but the connection of greater numbers of masses has not yet been explored.	This idea could offer a whole new level of engagement with ‘earthquake architecture’ - in terms of articulation and experience of building form.	As an alternative strategy in seismic design, this concept could affect future methods of building design.	Trees

4 CONCLUSIONS

The six ‘transferred concepts’ inspiring development, found after relatively cursory exploration, are worthy of future development. The paper also serves to demonstrate the value in taking a left-field approach to seismic engineering. Although these proposals are only lightly interrogated (no complex equations or shake-table tests involved), they may yet prove useful.

There are many benefits in exploring seismic resisting systems with this style of research approach: a design-based research process encourages a deep level of engagement with, and comprehension of, the topic; crossing between technological fields encourages the development of diverse and unpredictable ideas; and speculation can overcome the limitations of preconceived outcomes.

REFERENCES:

Alexander, R.M. & Goldspink, G. 1977. *Mechanics and energetics of animal locomotion*. London: Chapman and Hall.

Cimellaro, G. P. et al. 2004. Theory and Experimentation on Passive Control of Adjacent Structures, *13th World Conference on Earthquake Engineering*, Vancouver.

Hillier, V.A.W. 1990. *Fundamentals of Motor Vehicle Technology*, *4th Ed*. Cheltenham: Stanley Thornes Ltd.

Morishita, M. et al. 2004. Study On 3-Dimensional Seismic Isolation System For Next Generation Nuclear Power Plant – Vertical Component Isolation System With Coned Disk Spring, *13th World Conference on Earthquake Engineering*, Vancouver.

Peng, L., Yan, W. & Zhou, H. 2004. Test Study Of Adjacent Buildings Linked By High Efficient Damping System, *13th World Conference on Earthquake Engineering*, Vancouver.

Quiet Steel Advertisement. 2003. *Machine Design, October 23*. p. 48.

Sparks, J. 1972. *Animal Design*. London: British Broadcasting Corporation.

www.foxracingshox.com/website/TechnologyDesc.asp?Market=MBike&CategoryId=14&Id=2&count=1