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ENHANCING DYNAMIC PERFORMANCE OF LIGHTWEIGHT SUPERSTRUCTURES USING SUPPLEMENTARY DAMPING

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ABSTRACT: Ensuring that lightweight superstructures perform satisfactorily in terms of serviceability and safety requires close attention to how they respond to dynamic loadings in undamaged or damaged states. This reflects that their modal characteristics can cause accelerations levels under wind, seismic and other loadings that impinge on functionality, or propagate damage in extreme circumstances. Discussion here addresses application of supplementary damping technologies as cost effective ways of ensuring lightweight superstructures have desirable dynamic response characteristics in new or retrofit construction situations.

KEYWORDS: Damper devices, design, dynamic response, retrofit, safety, serviceability, superstructures, ultralight

1 INTRODUCTION

Tacoma Narrows Bridge, 1940

London Millennium Bridge excited by opening day crowd

Figure 1: *Unsatisfactory vibration performance (http://www.google.ca)*

Large physical objects like buildings, bridges and industrial structures oscillate as a result of surrounding ambient dynamic excitations. Mostly those motions are not perceptible to humans, and do not impinge on functionality or damage the objects. However this is not always the case, as everyday events and famous instances like wind induced disintegration of the Tacoma Narrows Bridge and disturbing swaying of London's Millennium Footbridge demonstrate (Figure 1). In most cases the source of the problem is failure on the part of the designer(s) to fully appreciate, or not appreciate at all, how structural systems can be excited in service or will respond to excitations [1,2]. Unlike with exotic structures, design of normal structures can involve little or no explicit design attention to possible dynamic response characteristics. In fact, best practice guidelines and design codes will often not bring attention to need to perform other than static force design analysis [e.g. [3-5]. Why this is the status in many instances, and defensible is that best practice guidance and codes reflect consolidated experience of how to create solution that should be satisfactory in terms of functionality and safety. Discussion here primarily addresses situations where use of lightweight construction methods (e.g. substitution of lighter structural elements for traditional ones) introduces need to explicitly address dynamic performances of superstructures. Exemplary of this is substitution of ultralight engineered wood products (EWP) like glulam framing and cross-laminated-timber (CLT) in lieu of relatively heavy reinforced concrete (RC) elements on which contemporary design practices are predicated.

Considering the example of CLT slab elements as substitutes for normal weight RC slabs in a 24 storey building, Figure 2 [6,7]. When the building has a structural steel framework, substitution of CLT for mechanically equivalent RC slabs (without other alterations) halves the total gravitational weight from 115.9 GN to 57.2 GN. When the building has a RC framework the same substitution reduces the total gravitational weight by about one third, from 166.1 GN to 108.4 GN. There are corresponding alterations in lateral modal masses, which reduce peak lateral and inter-storey drifts due to wind and seismic events. For example under the maximum credible earthquakes peak lateral and inter-storey drifts reduce by about 40% and 17% for the steel and RC frame systems

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respectively. Without need to enter into the details of the construction economics here, substitution of ultralight elements and substructures can yield substantial material and labour cost reductions, and/or be converted into safer and less damage resistant design solutions.

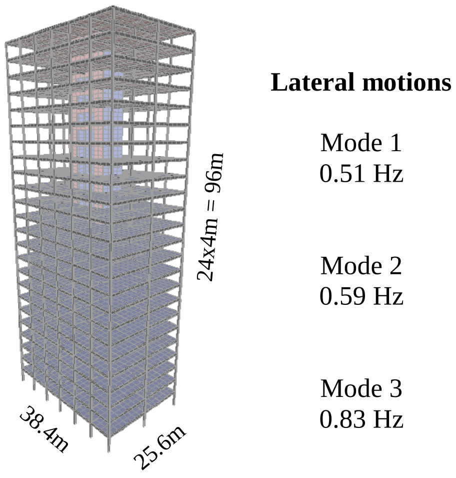

Figure 2: *24 storey building moment framework of structural steel or RC, and CLT floor and roof slabs (modal frequencies shown for RC framework)*

It is routine with tall buildings and long span and/or flexible bridges for designers to account for their dynamic responses. Even so however, design code requirements and engineering design practices are predicated on use of relatively heavyweight construction materials. Therefore it remains important when elevated substructures contain ultralight construction elements to fully consider the possibility of vibration serviceability issues arising, even when superstructure heights and spans lie below values where no previous problems have been found. Also to note is that apart from altering weight and modal masses, material substitutions and other design innovations can introduce semi-rigidities at inter-element interfaces that invalidate extrapolation of past experience of when problems may occur.

As the modal frequencies in Figure 2 illustrate, use of ultralight elements and substructures can lead to clustering of modal frequencies, which may amplify lateral accelerations to high levels, especially when mode shapes emphasise torsion about vertical axes. Such amplification of lateral motions has also been observed for mid-rise lightweight all timber framed building superstructures [8]. Lateral sway or inter-storey motions at system levels during windstorms or seismic events can result in accelerations that disturb building occupants or impede operation of equipment (e.g. elevators, machines). It is also prudent to consider whether alteration of gravitational weight could result in undesirable substructure performance characteristics like excessive vertical motions affecting serviceability of floor slabs.

Far from mean that use of lightweight or ultralight construction materials or elements is undesirable, it means that if that it is done it needs done carefully. Also, there are opportunities to alter structural responses in desirable ways, including through changes in construction details and addition of supplementary damping technologies. In all cases the objective is to reduce amplitudes of motions, thereby improving a superstructure's functionality and reducing structural demands on elements in load paths.

Amongst the possibilities use of supplementary dampers that incorporate moving masses is an attractive option. Such technologies typically have motion damping capabilities well beyond what can usually be achieved through other approaches. Some supplemental damping technologies are highly effective in control of both low amplitude motions associated with serviceability performance, and high amplitude motions associated with safety of structures. Also to note is that supplementary damping technologies can be non-invasive ways of retrofitting structures having unsatisfactory dynamic response characteristics [9].

The remainder of this paper addresses whether it is always necessary to accept that allowance for structural damage is a prerequisite to economic construction; reviews available supplementary damper technologies; and draws attention to the potential of distributed passive damper systems as cost effective and flexible ways of ensuring acceptable dynamic performance of new or retrofitted superstructures.

2 SAFETY PROTECTION OF SYSTEMS vs. OTHER STRUCTURAL OBJECTIVES

In the cases of slender and flexible superstructures it is usually valid to state:

> If a structural design is sufficient to control serviceability related dynamic motions, and substructures are sufficiently strong sizing of framing and diaphragm elements will rarely be governed by strength requirements.

This reflects that sizing to limit system motions will be sufficient to ensure that internal force flows through elements will not approach critical levels [6,7,10]. Typically material within slender and flexible structures is only stressed in the elastic response range, and it is usually possible to predict static or dynamic deformations with good accuracy.

However, in other situations (e.g. mid- and low-rise building superstructures, rigid bridge superstructures) it is common for element sizing to reflect desire to avoid rupture or instability, rather than desire to limit movements. This tends to mean that element sizing must balance mitigation of risk of rupture or instability with efficient use of construction materials and other facets of construction costs. Such balancing of priorities has underpinned development of nearly all construction systems and methods within and beyond the civil engineering sector. Throughout human civilization the enduring construction systems/methods have been those that mitigated the likelihood of damage, prevented unstable growth of any damage that did occur, moderated material utilization and other aspects of costs, and retained functionality on an indefinite basis [10,11], Figure 3.

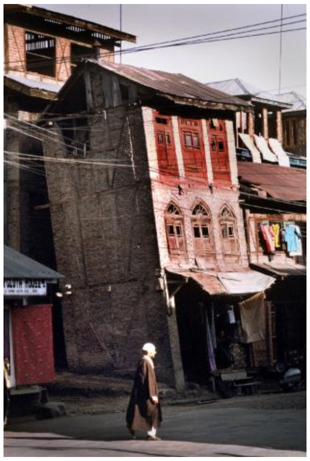

Figure 3: *A traditional timber-laced bearing wall house that has sustained severe seismic damage but not collapsed (courtesy of R. Langenbach)*

An essential characteristic of any structural system intended to sustain damage without collapsing is that it will toughen if locally damages due to rupture or instability of any one element or substructure within a load path [10,12]. To be safe against the possibility of a localised damage cascading into system level damage or failure, substructures need to have capability to absorb kinetic energy that flows through them as the result of strain energy released when damage forms. This can be achieved in various ways depending on the architecture and construction methods and materials employed.

Intuitively it might seem that construction of systems using ductile components (i.e. that when loaded in isolation exhibit substantial levels of ductility) will automatically exhibit ductile system and/or substructure failure mechanisms. Unfortunately this is not correct, because structural systems must obey dynamic energy equilibrium requirements throughout their lifetimes. When engineers design according to static energy equilibrium requirements, as is the norm premise underpinning contemporary material design codes [e.g. 3-5], there is in fact no surety that design solutions will have ability to prevent occurrence of damage or contain its growth`. The only way that such design codes can be applied with surety of avoiding collapse or widespread damage is to design structural systems with intent that their responses will remain in the elastic regime under applicable design loading scenarios.

In the modern context design practices that permit damage are ones that prescriptively enforce requirements for high levels of structural redundancy, or ones that enforce prescriptive methods intended to act as post-elastic response energy sink elements into load paths. Building code rules related to building regularity and avoidance of soft-storey behaviour that are linked to use of equivalent static design of seismic force resisting systems are an example of this [10]. Most common post-elastic response energy sinks include designing systems so that collapse mechanisms are controlled by formation of discrete plastic hinges and/or yield lines located directly within superstructure systems or at superstructure-foundation interfaces [13,14]. Other approaches include incorporation of stable buckling or frictional energy absorption elements placed directly within superstructure systems and at superstructure-foundation interfaces [e.g. 15,16]. Such practices are ineffective in terms of serviceability performance and are applied in the context of seismic design. With a few exceptions applicable to elevated bridge substructures, energy sinks devices for ensuring dynamic serviceability cannot be ones that have to be directly integrated into load paths (i.e. not be links within force resisting systems). Therefore, the most efficient approach is to employ supplemental damping devices having secondary mass/masses whose motion will counteract that of gravitational mass of force resisting systems and objects they support.

What level of protection structure systems are intended to have against occurrence of damage during design level events is a question usually addressed by engineers as part of a commissioning brief from the owners. However, this is usually subject to overriding regulatory minimums intended to limit the threats to people who occupy or use structures, and the potential to imperil neighbouring people and property [17].

Irrespective of whether design decisions are addressing serviceability or safety, incorporation of kinetic energy sinks is the only generally effective way of addressing effects of dynamic motions of elevated substructures and therefore structural systems to which they belong. As the discussion here illustrates only some technologies are globally effective. As highlighted below, those technologies that are effective are also ones that facilitate use of EWP (e.g. glulam, CLT) in innovative ways, and can enable realisation of new architectural forms and minimise construction costs.

3 EXISTING SUPPLEMENTAL DAMPING TECHNOLOGIES

Most efficient supplementary damping technologies are those that focus directly on enhancing dynamic responses of completed superstructures, rather than approaches that attempt to modify characteristics of construction elements.

Active mass dampers (AMD) can be an effective way of controlling lateral vibration motions of tall slender and otherwise flexible superstructures substructures caused by wind or earthquakes [18]. Their operating principle is that machinery moves one or more secondary masses under control from computer algorithms that anticipate movements of superstructures from dynamic feedback from accelerometers place at locations expected to experience high amplitude motions [19]. In some cases the mass/masses can be moved in arbitrary directions to counter quite complex compound modal motions. The 130m tall C Office Tower and the 58m tall Sendagaya INTES Office Building in Tokyo were the first buildings fitted with single and twin mass AMD, in 1993 and 1991 respectively [20,21]. The first triple mass AMD was installed in the 227m tall Shinjuku Park Tower, also in Tokyo in 1994 [21]. The drawback with such technology has been the associated expense, which has limited instances to landmark or otherwise important structures [22].

Tuned mass dampers (TMD) are a class of devices widely employed by automotive and power transmission industries. Uses of TMD to control motions of building and bridge superstructures have been effective but fairly limited, with the first single mass TMD being installed in the 553m tall CN Tower in Toronto in 1973 [20]. The first twin mass TMD was installed in the 244m tall John Hancock Tower in Boston in 1977 [20]. The Aratsu Bridge (cable-stayed) in Japan became the first bridge fitted with a TMD in 1987 [21]. Such devices are tuned to passively alter a vibration mode(s) or/and to add damping. The operating principle is that a suspended (or otherwise free to vibrate) secondary mass/masses will move out of phase with and counteract modal motions of superstructures. Sometimes the mass/masses is attached to viscous or friction damping elements. The mass installed at the 92nd floor of the Taipei World Financial Center is an iconic example of TMD technology [23], Figure 4.

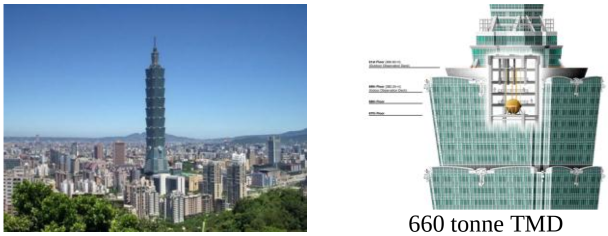
660 tonne TMD

***Figure 4:** Taipei World Financial Center (http://en.wikipedia.org/wiki/Taipei_101)*

To note is that so far both AMD and TMD have only been applied to systems where the vibration periods of the lowest order modes are quite long, i.e. in the order of 1 to 10 seconds [21]. The quite tall 24 storey building illustrated in Figure 2, that incorporates CLT slab elements, is in the same dynamic response category as structures having AMD and TMD. It is most likely however that the majority future structures incorporating ultralight EWP elements/substructures will exhibit shorter vibration periods and more complex modal interactions than structures to which dampers have been fitted.

Tuned sloshing dampers (TSD) have also been used to control motions of large structures, with the first instance being installation of 25 circular sloshing dampers in the 42m tall Nagasaki Airport Tower in Japan in 1987 [21]. First instances of rectangular unidirectional and double donut TSD were 16 devices install in the 136m Gold Tower in Udatsu, Japan in 1988 and 720 devices installed in the 159m tall TYG Building in Atsugi, Japan, in 1988 and 1992 respectively [21].

The TSD approach deserves attention because it can be an economic way of addressing serviceability and overload related aspects of dynamic performance of structures. The concept employed is that sloshing motion of liquid contained in an elevated tank(s) creates a sink for kinetic energy of a vibrating structure to which it is attached [24]. Energy in a vibrating system is dissipated by liquid being dragged across surfaces of TSD tank(s) and agitation of liquid that converts kinetic energy into heat energy. When TSD contain low viscosity liquid like water, the secondary mass that is the liquid moves out of phase with, and therefore counteracts motion of the supporting structure. If the frequency of water sloshing is equal to the fundamental or another natural frequency of a structure liquid will continue to move out of phase with the relevant modal mass. Frictional and turbulent sloshing energy conversions in TSD are equivalent to having a viscous or friction damped TMD.

***Figure 5:** One Rincon Hill tower in San Francisco [25]*

Like other devices TSD have usually been located at or near the tops of tall superstructures because that maximises motion of the secondary mass; and maximises the potential for sloshing which maximises damping efficiency, Figure 5. Strategies like shaping TSD tanks and adding baffles within them have been found to be successful ways of improving the sloshing efficiency of TSD [25]. Quite large fluid tanks have been installed in some tall slender buildings. Lee and Ng [26] suggested that a fluid mass in the order of 1 to 2% of the superstructure mass is sufficient for TSD to be effective, but use of relative fluid masses of more than 4% is also reported in the literature [27]. Economy of TSD stems from them having few parts and being relatively simple to construct. Like for other supplementary damping method, TSD have so far been applied to systems where the period of the energetic motions are quite large [21]. What is commonly stated to be limited their use is that that tanks occupy too much prime architectural space within buildings which adversely impacts returns on investments by building owners; and concerns about potential leakage of liquid. In the case of bridges an obvious limitation would be that in some climates liquids would have to contain antifreeze chemical raising considerable concerns about possible environmental pollution. The practicality of using TSD to control serviceability related motions of substructures like elevated floors in buildings, is much than for other technologies [28].

Making supplementary damping technologies suitable for broad spectrum application across civil engineering structures require that devices be:

- affordable to manufacture and install,
- not be too bulky,
- able to counteract complex dynamic motions,
- able to damp relatively short period motions (as might occur in systems incorporating ultralight elements and substructures), and
- practical to maintain.

Preferably devices would be one that can be retuned in circumstances like construction alterations or altered use of a structure (e.g. increased storage loads on floors). TSD or new types of devices that mimics their desirable attributes appear to be preferable.

4 LAB SCALE DEMONSTRATION OF SUPPLEMAENTAL DAMPING OF LIGHTWEIGHT SYSTEM

4.1 SCOPE AND METHOD

Model scale experiments were conducted to replicate lightweight superstructures having multiple ultralight elevated substructures. This was to find relationships between key modal response characteristics, mass of supplementary dampers and damper tuning frequency; and effects vertical distribution of the damper mass. TSD type TMD were employed because of their simplicity. The test structure had three storeys and consisted of a steel moment resisting framework welded at the bases to a massive steel plate, with plywood floor and roof diaphragms, Figure 6. It was 1.2m high and 0.4m by 0.4m on plan, with a total gravitational mass of 39kg. Nearly 70% of its mass was in the form of a steel plate rigidly attached to the underside of the top (roof) diaphragm. Modal mass and stiffness characteristics were selected to realistically mimic those typical of full-scale low- or mid-rise lightweight superstructures of types that might combine structural steel frameworks with CLT or other ultralight EWP slabs. Primary characteristics of the low order lateral vibration modes are summarised in Table 1.

Table 1: Low order modal frequencies (Hz) of superstructure without dampers

Mode type	Order of mode shape		
	1	2	3
Bending about x-z plane	7.4	50.3	116
Bending about y-z plane	8.2	51.5	115
Torsion about z axis	19.5	74.3	155

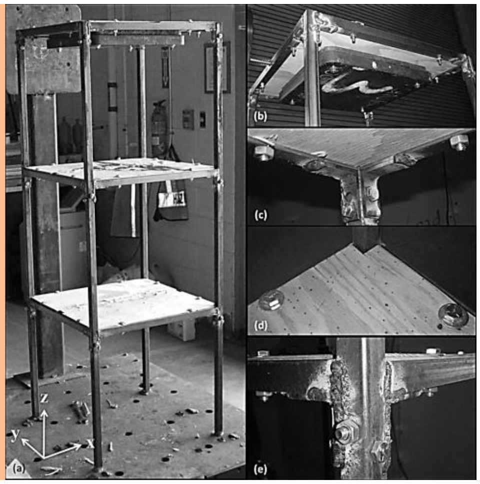

Figure 6: *Lab test structure*
a) completed structure, b) added mass plate, c) - e) typical framework and diaphragm junction

TSD used were water filled and sized to match desired combinations of sloshing frequency and mass. Water depths were selected to achieve sloshing frequencies in the range 2.8 to 7.2 Hz, which permitted investigation of using TMD exactly tuned or slightly off-tuned relative to low order modal frequencies or their sub-harmonics.

During study of the effectiveness of Distributed Tuned Damper (DTD) systems (i.e. location of dampers at more than one level in the structure) the total mass of water in tanks was varied between 0.77% and 4.78% of the total superstructure gravitational mass. This bracketed the range of mass that literature suggests is suitable for efficient application of TMD [26,27]. The reasonableness of the range studied had also been confirmed by theoretical analyses [29]. Apart from tests with TSD installed, experiments were conducted with plexiglass plates rigidly attached to the structure at matching locations. This enabled differentiation between effects of installing TSD and effects of simply adding mass to systems, with the difference being effects of damping within water filled tanks.

Forced vibration was used to dynamically excite the structure, using a shaker having a 5kg vibrating mass attached at the roof level. An accelerometer on the opposite face of the structure to the shaker measured horizontal acceleration. The forcing frequency was varied in the general vicinity the bending fundamental modal frequency of 8.2Hz, to determine the peak acceleration (a_{peak}) and effective viscous damping ratio (μ_{eff}) for each test configuration. Free vibration experiments were also conducted as reported by Erdle [29], who also explains other aspects of testing in detail.

4.2 RESULTS

Addition of up to about 5% of mass in the form of either TSD or plexiglass had quite small effect on the equivalent viscous damping characteristics of the system, with the value of μ_{eff} always being about 5.3%. However, when a mass of water greater than about 1% was added to TSD it had a clear influence in reducing a_{peak} measured at the roof level. This is shown by comparing a_{peak} values for water filled TSD versus plexiglass in Figure 7-a. The greatest difference between simply adding mass (plexiglass) and incorporating TSD was when the added mass was about 2% of the superstructure gravitational mass, when a_{peak} reduced 8% and μ_{eff} increased 7%.

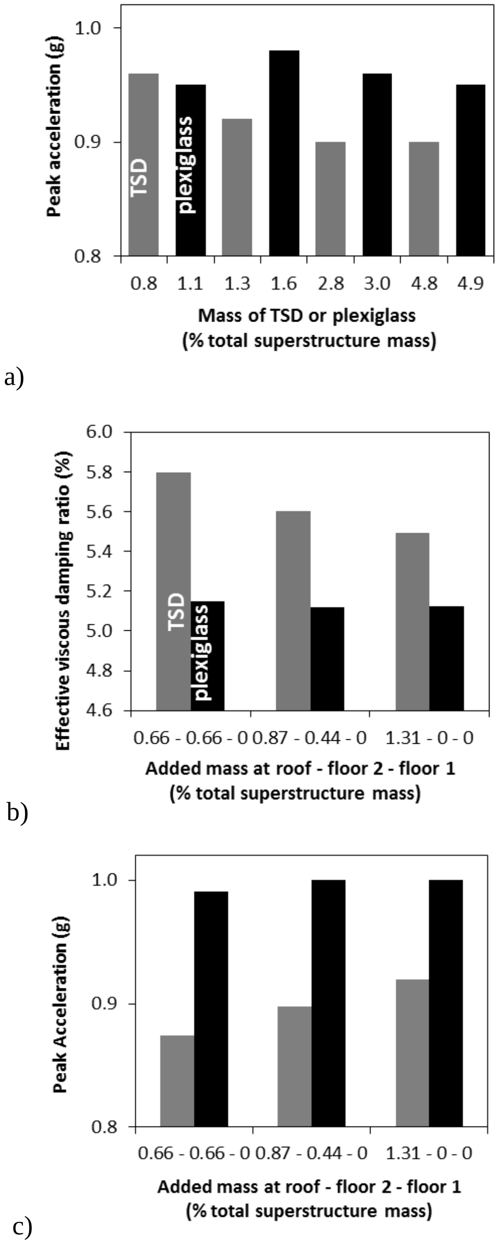

Figure 7: *Summary of selected results*

a) Effects of variation in adding TSD or plexiglass mass at the roof level

b) Effects of distributing added mass on μ_{eff}

c) Effects of distributing added mass a_{peak}

For cases where TSD had sloshing frequencies higher than about two-thirds of the fundamental bending frequency in the plane of excitation, addition of water in TSD always reduced a_{peak} and increased μ_{eff}, however this was mostly the result of adding mass which altered modal characteristics, rather than through improving damping due to water motion. Partly this was because the particular rectangular and bowl damper tanks employed had not been optimised in terms of their ability to cause sloshing action. Therefore there remains scope to further improve system performance through use of more efficient TSD or other TMD.

Experiments investigating the vertical distribution of TSD and plexiglass demonstrated that locating dampers strategically within superstructure is an efficient way of improving system response. Figures 7-b and 7-c show the effects of adding either dead mass or TSD at the levels of elevated floors as well as at roof level. In those figures, the notation 0.66 – 0.66 – 0 for example, means 0.66% of total superstructure mass was added at the levels of the roof and upper floor and none was added at the level of the lower elevated floor. Adding just dead mass (i.e. plexiglass) at levels of elevated floors level altered modal masses, frequencies, and mode shapes; while adding TSD also altered the modal damping. Shown a_{peak} reflect combined effects of all system characteristics on system responses at a particular location. Recognition of this is crucial to proper implementation of supplementary damping technologies, especially in cases where there is clustering of low order modal frequencies as illustrated in Figure 2. To put focus on how supplementary damping alters characteristics of individual modes would be a mistake in evaluating possibilities of distributed mass damper (DMD) systems.

Other prime facts to be gleaned from results in Figures 7-b and 7-c are:

- Using DMD it is possible to control displacement amplitudes of complex compound time history responses, as might occur during earthquakes and other events.
- Potential exist to design DMD systems that have arrays of TMD which control motions of different zones within superstructure systems (e.g. differential control tolerances for operating theatres and other zones in hospitals). This is addressed further in Section 5.
- The presently described experiments support suggestions that efficient TMD should have masses of between 1% and 2% of total superstructure gravitational mass. Those particular experiments indicated an optimal value of 1.3%, which is not fully consistent with previous suggestions [26,27]. This suggests that although there is latitude in where exactly an optimal choice of TMD mass will lie in specific situations, it is reasonable to expect that less than 2% of total superstructure mass will commonly

be sufficient to substantially improve a system’s dynamic response.

- TMD that are off-tune relative to a modal frequency or its sub-harmonics can be effective. There are of course limitations to the extent of that effectiveness, but by implication it is feasible to develop cost effective DMD systems capably of broad spectrum control of structural vibrations. This is addressed further in Section 5.

5 FULL-SCALE BROAD SPECTUM DAMPING

Researchers at the University of New Brunswick are in the process of developing DMD systems, and new highly efficient yet economic TMD devices. Figures 8 and 9 illustrate the concept of employing multiple damper arrays attached to elevated substructures within large superstructures. Underpinning principles and logic match what is discussed herein, with the result being capability to supress a broad spectrum of motions that could infringe on functionality or safety of almost any type of civil engineering superstructure. As part of this a premise the R&D team accepts is that it has now become for structural engineers in the civil engineering arena to seek technological solutions on an everyday (non-exotic) basis. More specifically, they accept that there is no need to simply attempt to control dynamic motions and associate force flows through structures by simply stiffening and strengthening those structures.

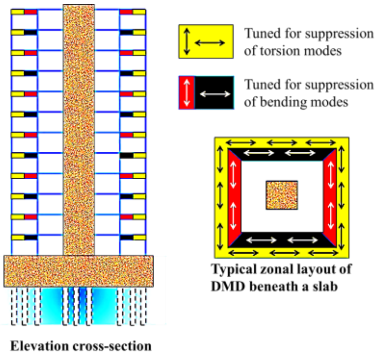

Figure 8: *Zonal placement of tuning of damper arrays in DMD system (courtesy of Advanced Construction Technologies III)*

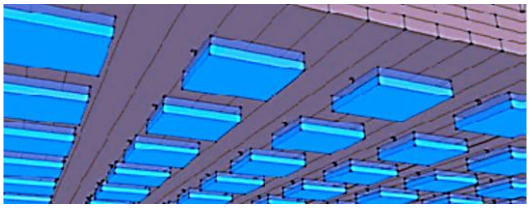

Figure 9: *DMD array on undersides of CLT floor slab (adapted from Weckendorf and Smith [30])*

Apart from what has already been discussed, it is to be mentioned that DMD systems are an effective way of counteracting adverse effects that physical irregularities introduced into structural systems for architectural or other reasons have on dynamic responses of structural systems. To illustrate, when ultralight EWP floor slabs are interspaced with much heavier RC fire floor slabs within tall building superstructures the resulting uneven vertical distribution of mass can amplify internal force flows and acceleration levels during seismic and other dynamic loading events [6,7,10]. A powerful application of DMD systems in conjunction with use of new ultralight materials and substructures is to facilitate creation of new architectural possibilities.

TMD of other damper technologies can provide highly cost design solutions or remedy behaviour of existing structures. Further details of work at UNB will be presented elsewhere.

6 CONCLUDING COMMENTS

Various types of supplementary damping devices have proven effective in terms of ability to protect building and bridge structures against effects of motions that could impinge on their serviceability or safety. Despite this, application of such technology has mostly been limited to relatively unusual situations involving slender or otherwise flexible systems. Yet, widespread use of supplementary damping technologies in non-civil engineering applications (notably the automobile industry) shows, it need not be prohibitively expensive to employ them. Arguably, partly why dampers are not routinely employed in civil engineering structures is that design practices have become excessively constrained, and too orientated toward simplified equivalent force and resistance methods and acceptance that structural damage is acceptable. However, introduction of performance-objective based design codes in various countries during recent years provides the means of changing such a status quo. Innovative engineers have opportunities to creatively go beyond the constraints of contemporary material design codes and be creative.

The table is ready to be set for widespread application of supplementary damping technologies to building and bridge superstructures that constitute the bulk of engineered structures. The essential question is whether or not engineers are willing to walk through the door of opportunity that could lead to use of new products like cross-laminated-timber in ways never previously contemplated as being accessible by timber-based products. If the answer is yes engineers could be on the cusp of a new structural engineering era just exciting as when at the end of the 19th and beginning of the 20th centuries innovative thinkers combined widespread availability of structural steel with innovations in structural engineering and invention of suitable elevators, into ability to realise architectural dreams. Then dreams included realisation of architectural modernism and skyscrapers. New dreams can include realisation of new architectural forms, and transition from designing structures that certainly will be damaged during events like earthquakes to one that will survive them unscathed.

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