State of The Art of Mitigation of Earthquake Induced Structural Vibrations Using Bioinspired Tuned Mass Damper

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Abstract - *Biological organisms possess the ability to prevent damage caused by natural hazards leading to disasters. Such an energy dissipation mechanism, 'Sacrificial bonds and hidden length' can substantially increase the stiffness in the constituent molecules of abalone shells and bone. Having been inspired by the usefulness and effectiveness of such a mechanism, which has evolved over millions of years and countless cycles of evolutions, the conceptual underpinnings of this mechanism is used to develop a bio-inspired Tuned Mass Damper. The original idea of using the mechanism called 'sacrificial bonds and hidden length' to develop a passive actuator has been demonstrated by embedding it in the cross-bracing of tall frame buildings. The passive actuator was effectively used to dissipate the energy through cross bracing within the structure to suppress vibrations due to earthquake and wind excitations. The current research focuses on using such concept of actuators but applied to both base isolators and tuned mass damper system.*

Key Words: Earthquake, Bioinspired, Tuned Mass Damper,

1. INTRODUCTION

An earthquake causes random movements of the ground, in all possible directions emanating from the epicentre. It is always accompanied by a horizontal vibration of the ground. The vibration of the soil vibrates the structures that rest on the ground, developing forces of inertia in the structure. As the earthquake changes direction, it can cause stress reversal in the structural components, that is, tension changes to compression and vice versa. An earthquake can generate large stresses, which can lead to large deformations, cracks and drifts, making the structure is not functional and unusable. The social, structural and economic damages caused due to an earthquake can be vastly reduced by preparing for such a calamity since earthquakes are almost unpredictable. From the engineering point of view, to prevent loss of life and property damages due to earthquakes, buildings are to be designed as earthquake resistant structures. In conventional systems, seismic energy is dissipated using inelastic mechanism s like flexural and shear hinging of elements like beams, columns and walls, axial tension yielding, brace buckling etc.

The recent trends towards constructing extremely tall and slender buildings to maximize the space utilization in urban areas have contributed to a new generation of earthquake sensitive structures. These tall structures are quite flexible and have very low damping values. The design of these structures involves resisting the lateral forces due to the earthquake as well as wind using the inherent strength, stiffness and damping of the system in combination with novel structural control methods. Since conventional methods are not much effective when it comes to the case of high rise buildings. There have been significant developments in the field of earthquake engineering in the past few decades and various devices like base isolators, mass dampers, liquid dampers, sensors and actuators etc., are used for structural control mechanisms.

2. TUNED MASS DAMPER

A tuned mass damper is a device which consists of a mass, spring and a viscous damper, which is attached to the vibrating main structure in order to filter out undesirable vibrations. The tuned mass damper is tuned such that its frequency is near the natural frequency of the main system. Hence the vibration of the main system causes the damper to vibrate in resonance and vibration energy is dissipated through damping in the viscous damper. The solution for determining the optimum tuning frequency and the optimum damping of the tuned -mass damper for undamped main systems subjected to harmonic external force, thereby reducing the steady-state response of the main systems to a minimum over a broad band of forcing frequencies, is given by Den Hartog (1956). The effectiveness of a TMD depends on tuning its stiffness and damping properties for a given primary structure and attached mass such that a significant kinetic energy is transferred from the main structure to the TMD mass and dissipated. Vibration suppression capacity of the TMD depends on its inertial property, i.e., larger the attached mass, greater will be its energy dissipation properties. However, in practice, the mass of about 0.5 – 1% of the total building mass is provided.

The effectiveness of a TMD is dependent on its tuning frequency ratio, mass ratio and damping ratio of the TMD with respect to the structure. TMDs are generally provided on the top of the building. However, multiple small tuned mass dampers can be provided along the height of the building to save space in the building.

However, the efficiency of tuned mass damper is constrained by the huge space requirement and practicality of placing a heavy mass on top of the structure. In order increase the efficiency, various control devices are attached to the mass.

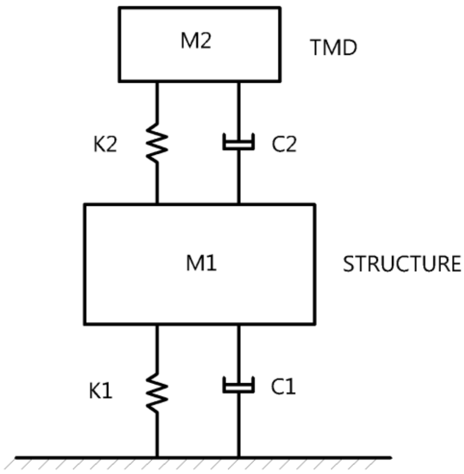

Fig -1: Tuned Mass Damper

3. BIOMIMICRY

Biomimicry is the study of emulation and imitation of nature, where it has been used by designers to solve human problems. For centuries, designers and architects have viewed nature as a huge source of inspiration. Biomimicry argues that nature is the best, most influential and guaranteed source of innovation for designers following the 3.85 billion years of evolution of nature, as it has a huge experience on problem-solving for the environment and its inhabitants. The emerging field of biomimicry deals with new technologies perfected by bio-inspired engineering at the micro and macro scales. Architects sought nature's answers to their complex questions about different types of structures, and they imitated many forms of nature to create better and more efficient structures for different architectural purposes. Without computers, these complex shapes and structures could not be imitated, Thus the use of computers tended to imitate and take inspiration from nature, using sophisticated and accurate tools for simulation and computing, making the imitation of natural models easier despite its complexity (Aziz et al. 2015).

4. LITERATURE REVIEW

A brief review of the state of the art of bioinspired structural control methods are discussed here. Other aspects of structural control like sensors for structural control, intelligent material systems, health monitoring and sensing damage are also studied. The development of tuned mass dampers and biomimicry for structural control and recent developments in bioinspired structural control methods are also presented.

4.1 STRUCTURAL CONTROL SYSTEMS

Structural control devices are introduced to reduce the response of a structure subjected to various dynamic lateral loads. They are divided into Passive, active, hybrid and semi-active control systems.

Housner et al. (1997) examines the state of the art in the control and monitoring of civil engineering structures and the connection between structural control and other areas of control theory, highlighting the differences and similarities successfully in the time period between 1990 and 1996. Saeed et al. (2013) studied the state of the art of structural control by comparing passive, active, semi-active and hybrid structural control techniques.

Various sections of structural control are discussed in the following section.

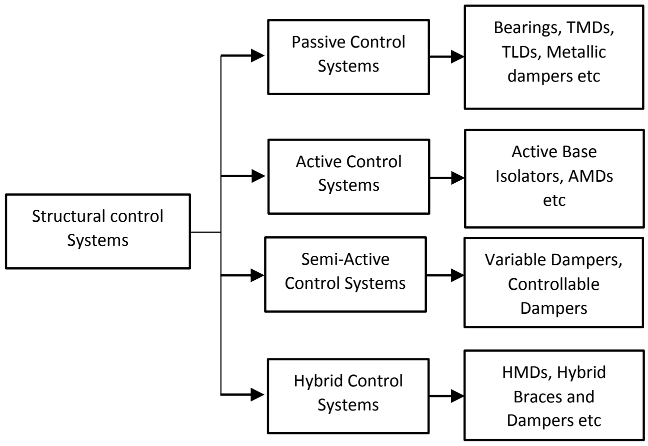

Fig -2: Structural Control Techniques

4.2 PASSIVE CONTROL SYSTEMS

Passive control systems are used to dissipate energy imparted due to dynamic forces such as earthquake loads, wind loads etc. by means of internal stresses, friction, yielding, plastic and elastic deformation of the damper. In passive control systems, no external energy is utilized for structural control.

Passive control systems include a range of materials and devices to improve damping, stiffness and resistance, and can be used both for natural risk mitigation and for the rehabilitation of aging or deficient structures. According to Cheng et al. (2008), the passive dampers are capable of providing higher damping for higher forces acting on the structure. It is also stated that the passive systems cannot adapt to different excitations as they are specifically tuned for a single excitation force. The response of a passive system is dependant on the response of the whole structure.

Base isolators are a type of passive control devices, which operates by introducing a layer of lower horizontal stiffness between the structure and its support. The layer of lower stiffness absorbs the energy through deformation and the deformation in the superstructure is reduced significantly.

According to De La Cruz (2003), the presence of that layer reduces the fundamental time period of the building separating the period of excitation from it. Ramallo et al. (2002) proposed smart base isolation system composed of low-damping elastomeric bearings and “smart” controllable (semiactive) dampers, such as magnetorheological fluid dampers to effectively protect structures against extreme earthquakes without sacrificing performance during more frequent, moderate seismic events.

Metallic Dampers uses yielding of metals to produce the damping effect during the action of a dynamic load. Kelly et al. (1972) and skinner et al. (1975) proposed the first models of metallic dampers and they used the inelastic deformation of metals like steel and lead for dissipation of energy. X-plate dampers (Pall, 1982) have equal energy dissipation in tension and compression braces as four links are present. Friction dampers works by dissipating energy through friction between two sliding bodies. It helps in reducing the velocity of motion of the structure. According to Markov (2008), Friction dampers are able to dissipate vast quantities of energy and is not affected by frequency of load cycles and temperature.

Viscoelastic dampers use viscosity of the fluid or shear deformation of the solid material to dissipate energy. The civil engineering application of VE dampers started with its usage on the world trade centre in1969 to cope the wind induced vibrations. A typical viscoelastic damper consists of a viscous layer sandwiched between steel plates was developed by 3M corporation. Examples of other VE dampers are cylindrical pot fluid damper and fluid viscous damper. Rakesh K Goel (2000) examined the use viscous damping to control excessive deformations in asymmetric-plan buildings during earthquake excitations. Constantinou et al. 1993 studied the structural applications of VE dampers and found it to be efficient in reducing response.

There are also other passive devices like Tuned Mass Damper (TMD), Tuned Liquid Column Damper (TLCD), and Tuned Liquid Dampers (TLD). The working of TMD is discussed earlier. The TLD is similar to a TMD, where the fundamental difference is in the energy dissipation mechanism which uses viscosity of the fluid and wave breaking concept. The sloshing of the fluid absorbs energy and is dissipated using viscosity of the fluid. According to Marko (2006), TLDs are no sensitive to the ratio of frequencies of both systems. TLCDs consists of a tube-shaped container consisting of a liquid attached to the structure. The energy dissipation takes place by the movement of liquid through an orifice. It is easy to implement and uses less space. In study by Marko (2006), it is found to be up to 47% efficient.

4.3 SEMI - ACTIVE CONTROL SYSTEMS

Semi-active control devices were developed from passive control devices. Unlike a passive device, semi active device uses some energy for its functioning. It consists of a control system which includes a sensor, a processor and an actuator in addition to the passive device. Though they are complex with respect to passive devices, they are easy to make, and is reliable and efficient than passive devices. (Cheng et al. 2008)

Semi-active Tuned Mass Dampers generally consist of a tuned mass damper fitted with a control system fitted either on the top of the structure or distributed throughout the building. They were developed for mitigation of wind vibrations in 1983. Yang (2002) developed a method to obtain instantaneous damping of a semi-active TMD. Chi-Chang Lin (2010) proposed a novel semi-active friction-type multiple tuned mass damper (SAF-MTMD) for vibration control of seismic structures using variable friction mechanisms and was able to keep all of its mass units activated in an earthquake with arbitrary intensity. The semi active TLD and TLCD concepts are in developmental stage. Baffle walls are used to adjust the tuning of TLDs by varying its angle (Cheng et al. 2008). Yalla (2001) developed a variable orifice for producing semi-active TLCD. semi-active variable stiffness (SAVS) device developed by Kobori et al. 1993, consists of a hydraulic cylinder, a double acting piston rod, a closed solenoid control valve and a tube that connects the two-cylinder chambers and were further enhanced by Spencer and Nagarajaiah in 2000, enabling variation of the stiffness independently and continuously, successfully producing a non-resonant system of a scaled structural model.

Magnetorheological (MR) dampers utilizes MR fluid (developed by Jacob Rainbow, 1949) or MR elastomers which are capable of changing their properties under the influence of a magnetic field (Larreq, 2010). These consists of magnetically polarisable particles dispersed in fluid or solid medium. Dyke et al. 1996 proposed a control strategy for optimal control of a MR damper against earthquake vibrations. The results showed it was more efficient towards earthquake vibrations than a linear active controller

4.4 ACTIVE CONTROL SYSTEMS

The limitations of passive control systems are adaptability and capacity of the system towards a dynamic excitation. They have to be tuned for each type of excitation, which due to the unpredictability of dynamic loads, is not practical. On the other hand, the semi-active devices are adaptable to different excitations, their efficiency is dependant on the passive device which it is based on. Thus, a need for active control systems arises.

Yao (1972) proposed an error activated control system, which can counteract an unpredicted dynamic load.

Active mass damper (AMD) are introduced to overcome the limitations of TMDs. They are evolved from TMDs with an active control mechanism to cater for a wider frequency range. The actuator is fitted between the structure and TMD to control the response of TMD. Nakajima et al. 2004 developed an AMD with a weight, a motor to drive the weight and a controller unit. Cao et al. 1998, designed an active mass damper to reduce wind effect on a communication tower in china. It involves the use of single mode approach for design evaluations. Wan et al. (1995) proposed a control with an active mass damper as the secondary control mechanism along with an active bracing system on a symmetric two-bay six-story building.

Active tendon systems involve prestressed tendons whose tension can be controlled using actuators. Abdel Rohman and Leipholz (1983) proposed an active tendon system for a building subjected to wind loading and is proved more efficient than a tuned mass damper. Okubo (1996) proposed an active control system for controlling the shape of a flexible space structure. The deflections are then determined and control forces are applied to restore the required shape.

Suzuki (2008) proposed the use of shape memory alloys (SMA) for tendons. The actuator involves a SMA tendon and a spring. The system was able to restrain free and forced vibrations in a flexible cantilever.

Active brace systems involve fixing an existing structure with an actuator to reduce the response of the building towards dynamic loading. There are also Active Tuned Mass Dampers which consist of standard tuned mass dampers fixed with control mechanisms. It was proposed by Chang and Soong in 1980. According to them, the control system enables using smaller seismic mass for structural control. The limitations being higher power and force requirement for actuators.

4.4 HYBRID CONTROL SYSTEMS

Hybrid control devices are created by serial and parallel combination of active, semiactive and passive control systems to attain maximum efficiency in structural control (Chang et al. 2008). Hybrid devices have higher efficiency and capacity compared to other types of structural control techniques. For hybrid devices, the energy consumption is less than active systems and reliability is higher according to Yan and Wu (2011) and De la Cruz (2003).

Hybrid Mass Damper (HMD) is a combination of active mass damper and a passive tuned mass damper. Energy required for working of HMD is very less compared to that of an AMD since the TMD is tuned for fundamental modes and the HMD is tuned for higher modes. Hence it is more efficient than an active TMD. The higher space requirement forms a limitation (Chang et al. 2008). Hybrid base isolators represents the majority of hybrid control applications in the United States, which can be subdivided into two types (Housner et al., 1997). The first system was proposed and tested by Yoshioka et al. (2002), this system uses MR fluid dampers on the superstructure instead of the active tendon in the second system. The second was studied and tested by Cheng and Jiang (1998); This system consists of a basic insulation system between the foundation and the structure and a system of active control of the tendons on the superstructure.

4.6 TUNED MASS DAMPERS

T Shimazu and H Araki (1996) studied the real state of the implementation of mass damper systems, the effects of these systems based on various recorded values in actual buildings against both wind and earthquake. The effects in relation with the natural period of buildings, the mass weight ratios to building weight, wind force levels and earthquake ground motion levels are discussed. Matsuzaki et al. developed a structural control device for long period building, which involves a two-mass system- a pendulum and a horizontal moving mass attached to pendulum. This enables the system to have a natural period greater than normal pendulums of same rod length. A Control force system was added, thus making it a semi active type. Pinkaew (2002) proposes damage reduction of the structure with TMD after yielding of the structure. Numerical simulations of a 20-storey reinforced concrete building modelled as an equivalent inelastic single-degree-of-freedom (SDOF) system subjected to both harmonic and the 1985 Mexico City (SCT) ground motions are considered. It is inferred that although TMD can significantly reduce damage to the structure, it cannot reduce the peak displacement of the controlled structure after yielding.

Chien-Liang Lee (2006) gives an optimal design theory for structures implemented with tuned mass dampers (TMDs) is proposed in this paper. Several TMDs (MTMD) installed on different building floors and the power spectral density (PSD) of the environmental disturbances are taken into account. He also proposed a numerical system to systematically obtain the optimal design parameters of MTMDs so that digital solutions converge to exact solutions as the number of iterations increases. The proposed optimal design theory is verified using an SDOF with a single TDG (STMD) structure, a five DOF structure with two TDGs and a ten DOF structure with an STMD and is found feasible.

I Saidi and A D Mohammed (2007) developed an economical and innovative Tune (TMD) mass damper using viscoelastic materials. Typically, a TMD consists of a mass, a spring, and a shock absorber that is attached to a floor to form a two degree of freedom system. They provided a detailed methodology for estimating the parameters required for optimal TMD for a given floor system and also describes the process of estimating the equivalent viscous damping of a viscoelastic material damper.

Christoph Adam and Thomas Furtmuller (2010) investigated seismic performance of Tuned Mass Dampers (TMDs) by a fundamental parametric study. Earthquake excited vibration prone structures are modelled as elastic single-degree-of-freedom oscillators and they are equipped with a single TMD. The TMD performance is assessed by means of response reduction coefficients and is found that TMDs are effective in reducing the dynamic response of seismically excited structures with light initial structural damping. Xiudong Tang and Lei Zuo (2011) investigated the feasibility of active self-powered vibration of structures with tuned mass dampers (TMD). Without consuming external power, the proposed self-powered vibration control strategy can provide better performance than passive TMD to mitigate building vibration induced by wind load. The TMD vibration dissipating element is replaced by an electromagnetic machine that serves as both an actuator and a harvester.

Angelis et al. (2011) studied the dynamic behaviour and the seismic effectiveness of a non-conventional Tuned Mass Damper (TMD) with large mass ratio. The device mass is increased up to be comparable with the mass of the structure to be protected, wherein the masses already present on the structure are converted into tuned masses, retaining structural or architectural functions beyond the simple control function. A reduced control model is introduced for design purposes and the optimal design of a large TMD mass ratio for seismic applications is then formulated. Alex Y. Tuan and G. Q. Shang (2014) studied the effects of a TMD on the dynamic structural responses of Taipei 101 Tower. The TMD frequency can be adjusted to match the predominant vibration frequency (usually the first modal frequency) of the main structure. A detailed dynamic analysis is performed to evaluate the behaviour of the structure-TMD system. The TMD in this building is much efficient in reducing wind-induced vibration.

Agathoklis Giaralis And Francesco Petrini (2017), coupled the classical linear tuned mass damper (TMD) with an inerter to suppress excessive wind-induced oscillations in tall buildings causing occupant discomfort. A parametric numerical study is undertaken involving a top-floor-TMD equipped planar frame accurately capturing the in-plane dynamic behaviour of a 74-story benchmark building exposed to a quasi-stationary spatially correlated wind force field accounting for vortex shedding effects in the across-wind direction. Results indicate that TMDI reduces peak top-floor acceleration more effectively than the classical TMD. Also, the inerter helps in dramatically reducing the TMD stroke and it can also be used to upgrade the performance of existing TMD-equipped tall buildings without changing the attached mass.

4.7 BIOINSPIRED STRUCTURAL CONTROL

Bioinspired structural control methods take inspiration from biological organisms to develop novel structural control systems. Yang et al. (2010), proposed a new strategy for structural control using 'Sacrificial bonds and hidden length' mechanism found in abalone shells and bones. The mechanism can substantially increase the stiffness and enhance energy dissipation in abalone shells and bone, the conceptual underpinnings of which is used to develop a bio-inspired passive actuator. A fundamental method for optimally designing such bio-inspired passive actuators for structural control is discussed. To optimize the bio-inspired passive actuator, a simple method utilizing the force–displacement–velocity (FDV) plots based on LQR control is proposed. The bioinspired actuator is designed for a three-storey structure proposed by Dyke et al. (1996). The force predicted by the mechanical model of actuator is given by,

$$f = \text{BIO}\,(x, \dot{x}) + C_0\dot{x}$$

where, BIO $(x, \dot{x})$ is force generated by the bioinspired mechanism. BIO $(x, x^{\cdot})$ is defined by

$$BIO\,(x, \dot{x}) = \begin{cases} f_{max} \text{ if } x \geq 0 \text{ and } \dot{x} \leq 0 \\ -f_{max} \text{ if } x \leq 0 \text{ and } \dot{x} \geq 0 \\ 0 \text{ if } x \cdot \dot{x} > 0 \end{cases}$$

A linear regression approach is adopted in this research to find the initial values of the desired parameters for the bio-inspired passive actuator. The numerical simulation with experimental validation, suggest that this bio-inspired passive actuator is comparable to state-of-the-art semi-active actuators.

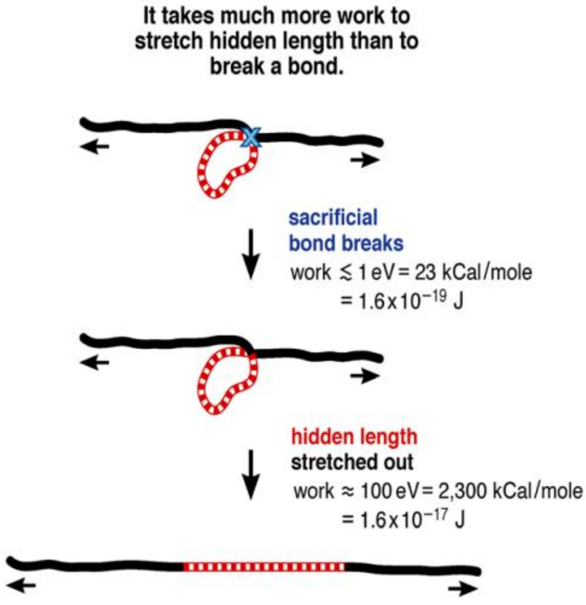

Fig - 3: Sacrificial bond and hidden length mechanism (Fantner et al. 2006)

Lieou et al. (2013) studied sacrificial bonds and hidden length mechanism in structural molecules that results in high fracture toughness of biological materials like bones, providing a mechanism at the molecular level for dissipation of energy. Here, a simple kinetic model that describes the breakdown of sacrificial bonds and the liberation of the hidden length, based on the Bell theory, has been proposed. A master equation governing the rates of fracture and bond formation was postulated and used to predict the mechanical behaviour of a quasi-one-dimensional set of polymers at different stretch rates. Breakthrough peak heights and maximum stretching distance have been found to increase with stretching speed and the theory also naturally allows the possibility of self-healing biological structures.

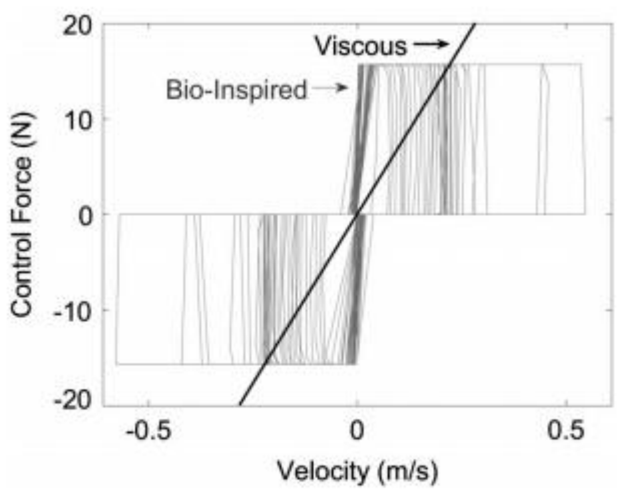

Fig - 3: Force vs Velocity behaviour of bioinspired actuator and conventional viscous damper (Kwon et al. 2017)

Kwon et al. (2015) developed bio-inspired passive negative spring actuator inspired by sacrificial bonds and hidden lengths is designed, fabricated and implemented in a three-storey structural model to test its performance and demonstrate effectiveness as a passive controller. The equation of motion (Craig 1981) of the model structure can

be written as

$$M_s\ddot{x} + C_s\dot{x} + K_s x = \Gamma f - M_s\Lambda\ddot{x}_g$$

Specifically, a unique design of a negative spring actuator is developed and combined with a viscous damper to present aspects of the force-displacement relationship of negative sacrificial bonding and hidden length.

The negative spring force as a function of the structural displacement, can be modelled mathematically as

$$F_s(x) = \begin{cases} sgn(x)\left(P - k_{sp}r\left\{1 - \cos\left[\sin^{-1}\left(\frac{|x|}{r}\right)\right]\right\}\right)\tan\left[\sin^{-1}\left(\frac{|x|}{r}\right)\right] & if\ 0 < |x| < r\sin\theta \\ sgn(x)(P - k_{sp}[r\{1 - \cos\theta\} + (|x| - r\sin\theta)\tan\theta]\}\tan\theta & if\ r\sin\theta < |x| \\ 0 & if\ x = 0 \end{cases}$$

The new actuator can produce great control forces, making the bio-inspired passive actuator practical for implementation in real structures. The results obtained from the numerical simulation were validated experimentally on a model structure. From the results, the bio-inspired passive negative spring actuator has a comparable structural control performance of state-of-the-art semi-active actuators.

Chen et al. (2015) proposed to develop a new strategy for base isolation using sacrificial bonds and hidden length mechanism. It is proposed to design the integration of this energy dispersion mechanism into a conventional linear isolator. A systematic parametric study was conducted to evaluate the influences of the properties of the isolation layer and the structure on structural seismic responses and the ideas gained are used to optimize the procedure for the design of a bio-inspired isolator. The function proposed by Yang et al. (2010) is followed for the design of bioinspired component. To demonstrate the advantages of this idea, the optimized bio-inspired isolation system is studied numerically by comparing first with passive isolators and a rubber bearing system. The isolator was found to perform better than conventional passive isolation systems, especially in low intensity earthquakes.

Kwon et al. (2017), developed a novel bioinspired actuator implemented in a tuned mass damper that mimics the sacrificial bond and hidden length mechanism, the effectiveness of the bioinspired actuator application is investigated with illustrative examples.

The piecewise damping function is given by

$$F(x_d, v_d) = \begin{cases} Fmax\left(\frac{2}{1 - e^{-k_{steep}\cdot x_d}}\right) & x_d \cdot v_d > 0 \\ 0 & x_d \cdot v_d < 0 \end{cases}$$

An SDOF was tested numerically and experimentally and up to 43% reduction in displacements were observed. The current bioinspired tuned mass damper, although passive, showed better performance in a numerical study involving a 76-storey benchmark building than the conventional passive tuned mass damper and was also comparable with the semi-active tuned mass damper in its capability of reduction in displacements and accelerations at various floors

3. CONCLUSION

As the height of the structures increases, the need for more efficient structural control systems increases. In the study various types of structural control methods in passive, active semi-active and hybrid techniques are discussed. The efficiency of such structures can be improved through inspiration from nature. In bioinspired structural control systems, the ability of biological organisms to prevent damages is mimicked. These systems are passive and has a higher energy dissipation capacity compared to the conventional systems. An energy dissipation system found in bones and abalone shells called 'Sacrificial Bonds and Hidden Length' is used to develop a passive structural control system. The efficiency of the system used in cross bracings, base isolators and tuned mass dampers are found to be higher than other passive and semi-active structural control systems.

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