RESEARCH COMMUNICATIONS

Orthodontic arch wires for seismic risk reduction

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Earthquakes are naturally occurring events demonstrating the power of nature and the catastrophic impact of such power on normal life. Development of new techniques and opting for new materials which are not traditionally used in civil-engineering structures, offer significant promise in reducing seismic risk. Superelastic Nitinol in the form of wires (orthodontic wires) is a common and well-known engineering material available with dentists all over the world. It belongs to the class of shape memory alloys (SMAs) bearing unique properties such as super elasticity and shape memory effect. The greater flexibility of the material drives many of its applications in the medical industry, but the use of this material in other fields is less known. This communication seeks the suitability of this material for structural applications, especially earthquake risk reduction. A study has been conducted to find the suitability of orthodontic wires in passive vibration control of structures. The super-elastic properties found in these wires are made use of in the development of vibration control devices of re-centering type. Protection of structures from damage during earthquakes can be addressed using passive protection devices designed to provide energy dissipation with re-centering capabilities. Possible applications lies in reducing the seismic risk of multi-span bridges, rehabilitation of heritage structures and protection of special structures of national importance.

Keywords: Earthquake risk reduction, orthodontic arch wires, passive vibration control, re-centering devices.

ORTHODONTIC wires, known as Nitinol, are made of NiTi alloy. Nitinol alloys are most commonly known for their super elasticity and thermal shape memory. While the term shape memory is used to describe the phenomenon of restoring a pre-determined shape through heating, after having plastically deformed that shape, the term super elasticity refers to the enormous elasticity of the alloys. An important feature of the super-elastic Nitinol alloys is that their loading and unloading curves are substantially flat over large strains. This allows the design of devices that apply a constant stress over a wide range of shapes. The orthodontic arch wire was the first wire to use this property, more specifically the constant unloading stresses. Nitinol wires unlike stainless steel wires are able to move with the teeth, applying a constant force over a broad treatment time and tooth position.

Due to distinctive macroscopic behaviour like super elasticity, shape memory alloys (SMAs) are the basis for innovative applications ranging from devices for the correction of tooth mal positions (orthodontic arch wires) to those for protecting structures from structural vibrations. The super-elasticity-based applications take advantage of the following features: (1) the possibility of recovering large deformations and (2) the existence of a transformation stress plateau, which guarantees constant stress over non-negligible strain intervals. Super-elastic properties of orthodontic wires have been established from experiments conducted and the salient features are highlighted here. The parameters influencing the seismic response have been tested and the material is found suitable for response-control applications in devices. Among the various types of passive vibration-control devices, re-centering

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devices were made out of these fine wires. Cyclic variable amplitude tests in these devices establish the behaviour. The capacity of the devices can be altered by changing the number of wires connected.

SMAs are a class of alloys that display several unique characteristics, including Young’s modulus—temperature relations, shape memory effects and high damping characteristics. While SMAs have been commercially available since the 1960s, their application has been limited. In most current applications, the temperature-induced phase change characteristic of SMAs is used. For some SMAs such as Nitinol (NiTi SMA), the phase change can be stress-induced at room temperature if the alloy has the appropriate formulation and treatment. The stress-induced shape memory property (known as super elasticity) is based on a stress-induced martensite formation. The austenitic phase of the material is stable before the application of stress. However, at a critical stress level the martensite becomes stable, causing yielding and a stress plateau (Figure 1). Since martensite is only stable because of the applied stress, the austenite structure again becomes stable during unloading, and the original undeformed shape is recovered. The two crystal phases in Nitinol differ in their crystal structures as shown in Figure 1. The austenite has a body-centred cubic crystal structure, while martensite has a parallelogram crystal structure (which is asymmetric) having up to 24 variations. Due to its parallelogram structure, the martensite phase is weak and can be easily deformed. Under external stress martensite undergoes a detwinning mechanism, which transforms different martensite variations to the particular variation that can accommodate the maximum elongation and this is responsible for super elasticity. In other words, super elasticity is related to the isothermal response of SMA specimens to applied mechanical loads. The ability of the SMA component to recover its original dimensions is an added advantage during cyclic loads. Since loading and unloading paths are different from each other (a hysteresis loop, which is identified with the stress difference of the loading and unloading), the area enclosed by the loop represents a certain amount of energy that is dissipated over the cycle.

Orthodontics is a specialized dental practice concerned with the movement of teeth to achieve an effective occlusion (the proper mating of the upper and lower teeth), and to provide a pleasing facial contour and appearance of the teeth. Tooth movement is accomplished by applying a force to the teeth in the direction of the desired movement. A relatively long-term application of corrective force of proper level will cause the tooth root to move within the supporting bone (the upper and lower jawbones respectively, the maxilla and mandible) to enable tipping, rotation, translation and other tooth movements needed to align mal-occluded dental arches. Corrective force is provided by the restoring force exerted by a stressed or activated elastic element such as flexible metal wire, a metal spring, or a band such as a ‘rubber’ band made of a material compatible with the mouth environment. The most common and useful elastic element in modern orthodontics is a metal arch wire of roughly U-shape, to conform to the array of teeth in each dental arch. The arch wire is coupled to the teeth by slotted orthodontic brackets secured to the teeth either by direct adhesive attachment, or by being fastened to a tooth band fitted over and cemented to the teeth. The arch wire is distorted or flexed when fitted into the bracket slots, and the resulting restoring force is exerted through the brackets on the teeth to urge them into proper alignment. To provide a constant corrective force, the super-elastic Nitinol wires are used. The highly resilient wire is employed in fabricating arch wires in order to apply the desired force for the intended correction. This mechanism generates a controllable force over an extended period of time and exhibits biological inertness. Andreasen has described the use of such alloys in fabricating arch wires and the advantages which they offer in orthodontic appliances. Birman and Humbeeck have provided comprehensive reviews on the properties of SMA materials. Since there are a number of new materials used for various applications, there is a need to investigate the engineering applications of SMAs for seismic protection of structures.

Properties which enable civil-engineering applications are as follows: (1) Repeated absorption of large amounts of strain energy under loading without permanent deformation. (2) Possibility to obtain a wide range of cyclic behaviour from supplemental and fully re-centering; to highly dissipating by simply varying the characteristics of SMA components. (3) Usable strain range up to 10%. (4) Extraordinary fatigue resistance under large strain cycles. (5) Greater durability and reliability in the long run.

The unique constitutive behaviour of SMA available in different forms has made it an attractive candidate for actuators and various structural control applications other than bio-medical, involving its shape memory effect. The first large-scale application of NiTi was in 1971, to connect a titanium hydraulic tubing in the Grumman F-14 aircraft. Since then, it has been used in a wide range of applications, such as enhancing buckling characteristics of composite panels, active acoustic control, active control of flow-induced vibrations, electrical connectors, thermal protection valves, switches, actuators, dental arches wire, dental implants, partial dentures, bone plates, thermosstatic mixing valves, air-flow controllers, etc. Savi and Mamiya have studied passive vibration control using pseudo-elastic behaviour of NiTi using a simple oscillator and showed that NiTi can be used for vibration control near the resonant condition. The study indicated that SMA components can be used for damage control in structures.

The experimental tests were carried out on austenitic wire samples of 0.4 mm diameter, which are mainly used for medical (dental) applications. The wires are available in spool form of approximately 4.5 m length. The compo-
sition of the wires was NiTi alloy with 55% Ni and the balance titanium-spooled NiTi. NiTi alloy wire with equiatomic composition possesses better dissipation property and higher resistance to corrosion and fatigue. Quasi-static and dynamic tests were conducted to evaluate the super-elastic properties and energy-dissipation capabilities under ambient temperature. A displacement-controlled actuator was used to perform the tests. The available information regarding the material was its latent heat and specific gravity, which were 14,500 J/kg and 0.234 lb/in$^3$ (6479.85 kg/m$^3$) respectively. No specific material-related information regarding heat treatment, etc. was available from the manufacturer. The tests were carried out under ambient temperature conditions around 27°C. Dynamic tests were carried out by applying sinusoidal cyclic deformation to the wire samples. The test parameters like deformation amplitude, frequency of loading and number of cycles were chosen taking into account their respective ranges of interest for seismic devices.

Initially quasi-static test on virgin SMA wire was carried out till failure of the specimen. The test was run in a position-controlled test set-up at constant rate of loading, 0.025 mm/s. Static tests on 1 mm diameter steel-binding wires (popularly used for reinforcement tying in India) were also carried out and the results have been compared. Figure 2 shows the stress–strain curve for quasi-static loading. The test programme included the quasi-static and dynamic tests on wire samples. Dynamic tests were conducted at constant and variable amplitude to evaluate the energy-dissipation capability and to find the number of cycles to failure. Tests were conducted by increasing the amplitude from 5 to 11 mm, thus increasing the strain from 5 to 9%. As it was difficult to attach an accurate instrumentation to measure strain on this fine wire of smooth finish, strain measurements were based on the actuator displacement. The frequency dependence on loading was also investigated during the experiment. The frequency of loading was varied from 0.5 to 3 Hz, at intervals of 0.5 Hz, as most of the earthquake applications fall within this range. Pre-strained wire performance was also investigated during the experiment.

Based on the engineering considerations, conceptual designs of the devices were prepared and the same were fabricated in Structural Engineering Research Centre, Chennai using wires without any pre-strain. A re-centering device has been prepared which has moving parts interconnected by these wires. During seismic cyclic actions at least one part ensures the tensile response and thus energy dissipation. Tests were conducted on these devices to variable amplitude loading in a displacement-controlled set-up.

Quasi-static (slow rate) tensile experiments clearly showed the super-elastic property of the SMA wire. Figure 2 presents the stress–strain curves obtained under quasi-static loading using a hydraulically driven test system (Instron make). The shape of the stress–strain curve
The yield stress of 597 MPa and ultimate stress of 1100 MPa were comparable with the idealized behaviour of SMA. If the material is unloaded after being loaded into the super-elastic region, the unloading portion of the stress–strain curve does not follow the loading portion, but follows a lower path back to the origin which indicates the transformation of stress-induced martensite back to austenite (Figure 3). Due to repeated cyclic deformation of the same amplitude, it has been observed that the hysteresis loops translate downward and become narrow. Consequently, the stress levels for the transformation decreased. Energy-dissipation capacity under constant amplitude loading remained the same up to 500 cycles; 20% reduction was observed in the next 500 cycles and around 30% reduction towards failure from the initial value. As our interest was on structural seismic applications, the number of cycles to be considered was less than 500, based on the Indian codal spectrum. The effect of increasing the amplitude and subsequent increased energy dissipation beyond 1500 cycles can be observed in Figure 4. Tests indicated that for 5 mm amplitude cycles, the wire could withstand up to an average of 1640 cycles before failure. It is interesting to note that the number of cycles for the same amplitude is not sensitive to the frequencies in the range 0.5–3 Hz (Figure 5). Also, the high fatigue resistance observed in SMA material helps reduce the post-earthquake repair costs, if dampers are made using these.

This material can successfully be used as re-centering mechanisms for seismic applications, because of its intrinsic capacity to undergo large deformations without showing any residual. Also its ability to generate hysteresis...
loops makes it a good choice as dissipating material. The design of Nitinol-based devices can be made choosing the mechanical properties such as transformation stress levels/plateau strength as design variables\textsuperscript{31}. Figure 6 shows the hysteretic behaviour of different types of devices that can be developed using the properties of Nitinol wire. Non Re-Centering Devices (NRC) can also be made using pre-strained wires. The following test results throw light on this aspect.

Figure 7 shows the hysteresis curve for the wire pre-strained at 5.5\% and cycled between 2 and 10\%. The equivalent viscous damping indicates the effectiveness of the material in vibration damping. This has been calculated based on the average energy dissipated per cycle and the damping values observed were also found to be significant. For 5.5\% pre-strain, one can see higher equivalent damping values. Cyclic variation of 4\% strain at 5.5\% pre-strain gave higher equivalent damping due to higher energy dissipation. An average equivalent damping ratio of 16\% was realized during the test\textsuperscript{12}. For wires without pre-strain, the equivalent damping ratio observed was in the order of 3\%. This is because during cycling, the compressive region does not contribute to energy dissipation. Tests on virgin wires showed lesser damping and energy-dissipation capacity and these results can be compared with those obtained under MANSIDE project\textsuperscript{13}. These results revealed the suitability of using pre-strained SMA wires in vibration control applications, especially for NRC (Figure 6). Normally pre-straining of wires in the device requires highly skilled labour, and maintenance becomes a difficult procedure. Hence a device was designed using wires without pre-strain, but tensioned during positive and negative movements. The device consists of two concentric pipes that move mutually when inserted in a structure subjected to seismic actions. There are three sets of projections or studs in each direction through which the super-elastic wires can be wound around. The special arrangement of studs and holes is such that for any positive or negative movement of the tubes, three sets of wires are always subject to elongation. Thus two independent groups of wire loops are obtained to act as the energy dissipating re-centering group. Cyclic tests were conducted on the device at 0.5 Hz frequency (sinusoidal), in which three smaller diameter wires acted as a group. Wires of 0.4 mm diameter posed great challenge in fixing and a skilled fastening mechanism has been utilized.

Another interesting observation is that the hysteresis loops became narrow and translate upwards when there is an increase in strain amplitude, while the branches of the curve relevant to the phase transformations harden, thus yielding an increase in the stress levels (Figures 4 and 8). This is true for pre-strained wires as well as those without pre-strain. This trend was observed in the case of cycling around 7\% pre-strain, as the strain reached the end of the transformation range around 10\%. This phenomenon is related to the elastic deformation of the de-twinned martensite found at the end of the phase transformation. This is a favourable aspect in seismic applications as the system stiffens rather than softening if the expected design seismic action is exceeded, thus ensuring a good control of displacements. An increase in energy dissipation can be observed as the cyclic strain amplitude increases. Various amplitudes were tried at 7\% pre-strain and similar trends as explained above were obtained (Figure 8).

The best use of the material is for re-centering mechanisms since their pseudo-elastic behaviour is effective for very large ranges of deformation. Hence among the various options available as in Figure 6, a re-centering device
was made using virgin wires and tested in the laboratory. The applied loading history is shown in Figure 9. The devices developed showed re-centering capability favourable to seismic applications. An average equivalent damping ratio of 12% was realized during the cyclic tests. Variable amplitude tests on the devices indicated that it was suitable during seismic actions, as it demonstrates different structural properties for different horizontal forces. A similar trend as explained above was obtained for the device too. Figure 10 shows the testing of the device in a 5T capacity Instron testing machine. The test was conducted in a displacement-controlled set-up. The energy-dissipation capability per unit displacement remained constant. Under low horizontal forces, devices are stiff and allow for no significant displacements. Under high horizontal actions such as an earthquake, device stiffness reduces for controlled displacements, and for extremely intense horizontal loads their stiffness again increases to prevent collapse. The aforementioned behaviour is useful for seismic risk reduction for varying performance levels, if incorporated into the structures. A combined use of these devices with steel – a traditional dissipative material – will open up other interesting applications in seismic risk reduction.

The properties observed in the material allow developing devices for seismic protection of structures. The device has the ability to dissipate significant energy through repeated cycles, without significant degradation or permanent deformation. Their usable strain range is of the order of 6–8%, which provides them with high energy dissipation per unit mass of material. Re-centering devices gain the best mechanical characteristics of both quasi-elastic devices (e.g., rubber isolators) and elastoplastic devices (e.g., steel hysteretic dampers). While recovering the initial position of the structure with a good control of the displacements, they put a threshold to the force transmitted to the super-structure, thus controlling the forces well. The full possibility of designing the

Figure 8. Typical sketch showing hysteretic curves obtained at 7% pre-strain with variable amplitude.

Figure 9. Performance of a re-centering device under variable amplitude cyclic loading.

Figure 10. Experimental set-up for testing of the device.

Figure 11. Possible applications of the devices. (i) Restrainers in bridges; (ii) Diagonal braces in buildings; (iii) Cable stays.
mechanical behaviour combining the self-centering and energy-dissipation capability, permit calibration of the desired features to fit specific needs. The availability of these features opens considerable room for improvement of the structural system design. They can be fitted into structures as diagonal braces or seismic dampers, as shown in Figure 11.

A variety of hysteretic behaviour can be obtained from the material tested and its application can be made suitable for seismic devices like re-centering, supplemental re-centering and non re-centering devices. The orthodontic wires tested showed excellent fatigue resistance. Cyclic behaviour of the wires, especially energy-dissipation capability, equivalent viscous damping and secant stiffness were not sensitive to the number of cycles in the frequency range of interest (0.5–3 Hz). The stiffening observed in the wires for higher amplitude loading ensures a good control of displacements in case of strong seismic events. The re-centering capability is an added advantage. Pre-strained super-elastic wires show higher energy-dissipation capability and equivalent damping over the available strain range of 2–10%. Among the various types of devices, the wire under tension mode can be selected between pre-strained and non pre-strained wires for possible application in various kinds of vibration control devices in structural systems. One such device fabricated and tested in the Structural Engineering Research Centre, Chennai renders promising applications for seismic response reduction/retrofit measures in structures, including bridges.

5. Andersen, U.S. patent number 4037324.

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Wild cane as a renewable source for fuel and fibre in the paper industry

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The Sugarcane Breeding Institute, Coimbatore in collaboration with Tamil Nadu Newsprint and Papers Limited (a bagasse-based paper mill), is exploring the utilization of wild cane in energy generation and as an alternate source of raw material for the paper industry. The germplasm collection of the wild cane species, Erianthus arundinaceus, was evaluated for its performance under cultivation, biomass production, stalk yield, fibre content and juice quality. Out of 88 clones evaluated, 23 with high fibre–pith ratio were selected. Based on proximate analysis, six clones were selected for further tests and trials. This species has the potential to yield high biomass for the production of energy through cogeneration, alcohol through bio-fermentation of its juice and bagasse (stalks after extraction of juice) as raw material for paper manufacture. Energy content of biomass was assessed by estimation of the calorific value. Studies on fibre content, bagasse yield, biomass yield and pulping showed that this species is superior to sugarcane as a source of energy and fibre. So far no systematic evaluation of this naturally growing species has been done for its biomass production, energy content, fibre yield and juice quality, and no commercial cultivation for its co-products has been attempted.

Keywords: Bagasse, energy, fibre, fuel, wild cane.

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