

(19)



(11)

EP 2 450 506 A2

(12)

EUROPEAN PATENT APPLICATION

(43) Date of publication:

09.05.2012 Bulletin 2012/19

(51) Int Cl.:

E04H 9/02 (2006.01)

(21) Application number: **11008881.2**

(22) Date of filing: **08.11.2011**

(84) Designated Contracting States:

**AL AT BE BG CH CY CZ DE DK EE ES FI FR GB
GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO
PL PT RO RS SE SI SK SM TR**

Designated Extension States:

BA ME

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(30) Priority: **09.11.2010 IT BA20100045**

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(54) **System including a shape-memory alloy device**

(57) System including at least one shape memory alloy based device (1) and at least one metal chain (6) assembled to each other in series, applicable in building

industry to thrusting structures, able to optimize the response of the above mentioned chain to thrusting loads and subjected to external undesirable thermal and/or seismic effects.

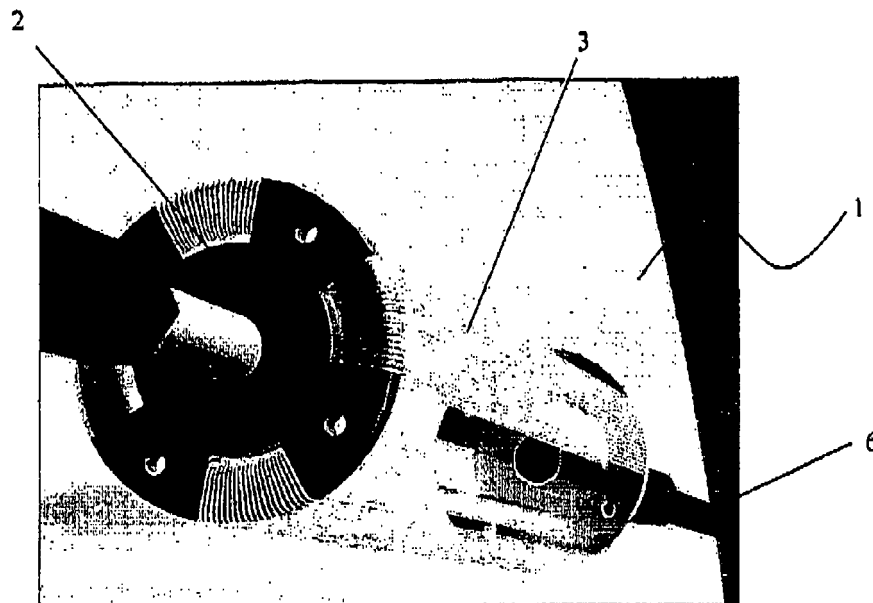


Figure 3

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Description

[0001] The present invention relates to a system including at least one protection device based on the typical properties of shape memory alloys (in the following called SMA for simplicity) in series to a metal chain, applicable in building sector to thrusting structures such as arches, vaults or bridges aiming at adsorbing their thrust in an optimal and more efficient way with respect to technologies commonly employed.

[0002] At the state of the art it is known that the use in these sectors of traditional metal chains or other kinds of metal elements does not resolve several problems such as sensibility to thermal variation, difficult stretching calibration, bad behavior in seismic conditions, and so on. These problems can be overcome through the integration in these structures of SMA based devices, properly designed to enhance the behavior of traditional metallic chains, both in service and in seismic conditions.

[0003] Some applications that make use of SMA based devices are also known, but these applications are purposely designed for specific structures and load types and then implemented in such structures using special devices, which are independent from the primary structural elements. For example the patent EP1016725 relates to a dissipating and load limiting device for the protection, the restoration and the construction of civil and industrial structures with high resistance against undesired static effects, seismic, aeolian and dynamic effects, characterized by the fact of including a series of shape memory alloys wires.

[0004] The main objective of the above mentioned invention is to assure the stability of the structures to whom it is applied above all against external effects (in particular earthquakes) that can produce vibrations for the structure.

[0005] The device of the present invention, instead, aims at reducing above all the undesirable effects due to daily and seasonal thermal variations, assuring at the same time a satisfying seismic behavior of the whole structure, even in case of high intensity earthquakes.

[0006] Some of the goals that the invention aims at achieving can be summarized as follows: (i) to control tension in the chain in the stretching phase; (ii) to control tension in the chain in serviceability conditions when room temperature changes; (iii) to avoid the yielding and/or the instability of the chain in case of high intensity earthquakes; (iv) to limit the force transmitted by the chain to the structure in case of earthquake.

[0007] The object of the present invention achieves the goals above illustrated, as well as the further goals that will emerge from the following detailed description, since it relates to a system, applicable in building industry to thrusting structures, including at least one shape memory alloy (SMA) based device, at least a metal chain and at least an anchor plate, characterized by the fact that the stress changing in the chain, caused by variations of the room temperature or by seismic phenomena, are limited and controlled by the thermal and mechanical behavior of the mentioned SMA device, which results to be antagonist with respect to the chain one.

[0008] These and other advantages will result in the detailed description of the invention that will refer to the drawings from 1/4 to 4/4, where a manufacturing example, absolutely not restrictive, of the present invention (application in case of arches) will be shown. In particular:

- Figure 1 is an implementation example of chain for arch equipped with a SMA based device;
- Figure 2 is a detailed sight on the SMA based device;
- Figure 3 is a 3D rendering of the SMA based device ;
- Figure 4 is a schematic representation of the behavior of the SMA based device assembled in series with a metal chain subjected to both increase and reduction of temperature;
- Figure 5 is a schematic representation of the behavior of the SMA based device assembled in series with a metal chain subjected to both (a) increase and (b) reduction of the temperature adopted for dimensioning SMA wires length in serviceability conditions;
- Figure 6 is a simplified model for the evaluation of the seismic response through spectral analysis defined by the stiffness factors (a) K_{eq} and (b) K_{eq}^* ;
- Figure 7 is the numeric model adopted in the simplified procedure for dimensioning the SMA based device subject to seismic actions.

[0009] As shown in Figure from 1 to 3, the basic idea of the present invention is a SMA based device, not much invading, cheap and able to enhance metal chains performances, both in serviceability conditions and under earthquake.

[0010] As shown in Figures 1 and 2, the whole device is generically indicated with 1 and is constituted by several superelastic pre-stretched SMA wires 4, by at least a couple of wires anchor plates 2, eventually also by a case for the above mentioned wires 3, and by one or more sleeves 5 for the wires pre-stretching. 4. It is clear that the above-mentioned parts may be numerous depending on designed device typology, which depends itself on the designed structure type which the device will be applied to. Therefore the SMA based device now described may be implemented (for example in the not restrictive case shown in Figure 1) in series to a common steel chain 6, anchored itself to its own anchor plate 7.

[0011] The chain 6 stretching will be made by pre-stretching the SMA wires to chain and devices already assembled

and fixed to the anchor plate 7. The wide horizontal plateau associated to the martensitic transformation permits to calibrate with extreme accuracy the tension in the steel chain in the pre-stretching phase.

[0012] To this purpose it is necessary to observe that the pre-stretching operation is very slow. Consequently the martensitic transformation happens through a isothermal process in which the associated stresses remain almost constant. Because of the pre-stretching effect, therefore, the SMA wires, initially in austenitic state, will undergo a partial martensitic transformation. So at the end of the stretching operation, the phases austenitic and martensitic coexist, approximately in the same proportion. The main goal that the object of the present invention aims at reaching is to limit and control the stress changing in the steel chain caused by the room temperature variations taking advantage of the thermal behavior of SMA wires. In effects, the behavior of superelastic SMA wires results to be antagonist with respect to the steel chain one. At this purpose in Figure 4 it is shown how, increasing temperature, the stress drop in SMA wires, due to the shortening induced by the steel chain elongation, is compensated by an. upward shift of the σ - ϵ curve of the SMA, which suffers an overall variation of the tensional state equal to $\Delta\sigma^+$. On the contrary, reducing temperature, the temperature increase in the SMA wires, due to the strain increase induced by the steel chain shortening, is compensated by a downward shift of the σ - ϵ curve of the SMA, which suffers an overall variation of the tensional state equal to $\Delta\sigma$. Stress variations shown in Figure 4 produce force variations in the steel chain, put in series with the SMA device, certainly smaller than those suffered by the chain alone. Together with the "thermal" aspect, the use of a SMA based device provides also undoubted advantages from the point of view of the protection of undesired events (for example collapse) in case of earthquake. In fact, in high seismicity zones, the SMA based device permits to prevent collapse taking advantage of the SMA superelastic properties, in particular hysteresis and viscose damping. In order to obtain wide hysteresis loops under earthquake and to be able to dispose of high equivalent viscose damping values is suitable to pre-stretch the wires until they reach the middle of martensitic transformation line (2-3%). The use of pre stretched superelastic SMA wires, after cycling around the central part of their hysteresis loop, allows to increase significantly the equivalent viscose damping, especially after the effective stiffness reduction associated with a complete strain cycle. Besides the device can limit also possible strain increases caused by earthquakes of unexpected intensity thanks to the stiffness increase for high strains (6-8%) available at the end of the direct transformation. Finally the pre-stretching allows to avoid the chain instability, being able to arrange possible negative strains due to an approaching between the ashlars where the anchor plate have been anchored. In order to reach the goals now described is necessary to proceed with the necessary design steps for the implementation of the SMA based device. Mainly these steps consist in the optimal evaluation of the SMA wires parameters such as wires number, diameter and length of wires both in serviceability conditions and under earthquake. The diameter and the number of SMA wires to adopt derive from the value of horizontal thrust (denoted with H in the following) to be adsorbed due to gravitational loads only. The wire length, instead, will be optimized considering the thermal and seismic behavior of the chain provided with the proposed SMA device through proper numeric models. The proposed numeric models take into account the thermal and mechanical behavior of SMA wires obtained through preliminary experimental loading and unloading tests kept on until the finishing of the transformation of the direct phase (about 6% strain) and carried out at various strain rates (with frequency between 0.01 Hz and 0.5 Hz) and air temperatures (between 0°C and 40°C). In order to enhance the SMA wires thermal behavior it is suitable to subject the wires to a preliminary training step so that to reduce the hysteresis loop amplitude and to increase work hardening. Regarding the number and the diameter of the SMA wires as initial hypothesis the steel chain and the SMA wires are assumed to be in series and result therefore subjected to the same load. The SMA wires number (n_{SMA}) needed for adsorbing the horizontal thrust H transmitted by the arch must be evaluated through the relationship:

$$n_{SMA} = \frac{H}{\frac{\phi_{SMA}^2}{4} \cdot \pi \cdot \sigma_{SMA}^0} \quad (I)$$

having denoted with ϕ_{SMA} and σ_{SMA}^0 the wires diameter and the initial pre-stretching stress, respectively. Clearly, wires diameter will be chosen taking into account of the commercial diameters (typically between 1 mm and 2 mm). The σ_{SMA}^0 value, instead, is a function of the mechanical properties of the adopted wires, assessable through laboratory tests. Obviously, σ_{SMA}^0 depends on the temperature at which the pre-stretching is carried out.

[0013] The SMA wires length must be evaluated taking into account the effects induced by both thermal variations and seismic actions. Initially it is possible to estimate the SMA wires length through two simplified procedures which take into account the above mentioned induced effects. In particular seismic effects will be evaluated adopting for the monthly medium temperature the maximum ($T_{med,max}^*$) and the minimum ($T_{med,min}^*$) values; while for thermal effects the ranges associated to the maximum ($T_{day,max}$) and minimum ($T_{day,min}$) daily temperatures will be taken into account. The relationships that will be proposed in the following for the simplified procedures are used for the only purpose of

having an idea of the SMA wires length needed for the device correct working. It is clear that the effectiveness of the length evaluated in this way will be verified through proper numeric models used to consider in a more rigorous way the effects due to earthquake and to thermal variations in serviceability conditions.

[0014] In order to evaluate the SMA wires length in serviceability conditions, taking so into account the thermal effects that may be produced in the steel chain connected to the device object of the invention, let's suppose, first of all, to carry out the pre-stretching operation at a temperature T_0 equal to 20°C. Denoting with ΔT the maximum expected temperature range, the length variation ΔL_s for steel results to be equal to:

$$\Delta L_s = \Delta T \cdot \alpha_f \cdot (L - L_{SMA}) \quad (II)$$

being α_f the steel thermal expansion factor ($12 \cdot 10^{-6} \text{ }^\circ\text{C}^{-1}$), L the whole steel chain length and L_{SMA} the SMA wires length (unknown). It is worth to underline that the length L results to be equal to the arch span increased, at both sides, with the piers thickness. After a positive (negative) thermal variation the steel chain will undergo a lengthening (shortening) ΔL_s to which will correspond, for congruence, a shortening (lengthening) ΔL_{SMA} of the SMA wires that can be express through the relationship:

$$\Delta L_{SMA} = L_{SMA} \cdot \Delta \epsilon_{SMA}^* \quad (III)$$

in which $\Delta \epsilon_{SMA}^*$ represents the SMA wires strain variation, due to the temperature variation.

[0015] For congruence it must result:

$$|\Delta L_s| = |\Delta L_{SMA}| \quad (IV)$$

[0016] By substituting expressions (II) and (III) in (IV) it is possible to express strain variation $\Delta \epsilon_{SMA}^*$ as:

$$\Delta \epsilon_{SMA}^* = \alpha_f \cdot |\Delta T| \cdot \left(\frac{L}{L_{SMA}} - 1 \right) \quad (V)$$

[0017] Together with the shortening (lengthening) of SMA wires due to steel chain lengthening (shortening), nevertheless, an increase (decrease) of the stress level in SMA wires is registered, in virtue of the particular thermal and mechanical behavior of the material. In theory the stress decrease (increase) in SMA wires due to the shortening (lengthening) of wires induced by the chain is compensated by the stress increase (decrease) due to the temperature increase (decrease) (as shown in Figure 5). It is worth to underline that stress variation shown in Figure 5 provides force variations in the steel chain, assembled in series with the SMA device, certainly lower than the ones suffered by the only chain. The minimum SMA wires Length needed to assure a satisfying thermal behavior can be deduced assuming the finishing of direct phase transformation ($\Delta T < 0$) or inverse ($\Delta T > 0$) after the maximum thermal variation expected. Referring to Figure 5, denoting with ϵ^0 the wires pre-stretching strain (at temperature T_0), with $\epsilon^{AM,f}$ the strain corresponding to the finishing of the direct phase transformation (at temperature $T < T_0$) and with $\epsilon^{MA,f}$ the strain corresponding to the finishing of the inverse phase transformation ((at temperature $T > T_0$), the minimum SMA wires length ($L_{SMA,min}$) results to be equal to:

$$L_{SMA,min} = \frac{L \cdot \alpha \cdot |\Delta T|}{\Delta \varepsilon_{SMA,max}^* + \alpha \cdot |\Delta T|} \quad (VI)$$

where:

$$\Delta \varepsilon_{SMA,max}^* = \min(\varepsilon^0 - \varepsilon^{M,f}; \varepsilon^{A,f} - \varepsilon^0) \quad (VII)$$

[0018] Expression (VI) is a pre-design formula that does not perfectly take into account of the interaction between the SMA wires and the steel chain.

[0019] Once fixed the length and the number of wires to use, it is possible to evaluate the force variation ΔF of the system "chain+SMA" through the relationship:

$$\Delta F = \Delta \sigma_{SMA} \cdot A_{SMA} \quad (VIII)$$

where A_{SMA} represents the whole cross section area of the SMA wires adopted and $\Delta \sigma_{SMA}$ is the variation of the stress state in the wires after the imposed thermal variation.

[0020] The force variation due to the thermal variation of the system constituted by the only steel chain, instead, is evaluated by multiplying the cross section area of the steel chain for the stress variation evaluated with the relationship:

$$\Delta \sigma = E \cdot \alpha_f \cdot (\Delta T) \quad (IX)$$

where α_f is the steel thermal expansion factor equal to above $12 \cdot 10^{-6} \text{ } ^\circ\text{C}^{-1}$ and E is the Young modulus of steel. In order to evaluate the SMA wire length in case of earthquake, the proposed design approach is based on an iterative procedure made up of five steps, that makes use of a simplified arch model (Figure 6) characterized by two "V upside" struts, with an hinge at the top and connected at the base through an element which simulates the equivalent stiffness (k_{eq}) of the system in series chain + SMA based device. The arch participating mass (m) is itself concentrated at the top. Seismic vertical and horizontal oscillations of the considered model may be studied referring to an elementary oscillator of mass m and equivalent stiffness (k_{eq}^*) equal to:

$$k_{eq}^* = 2 \tan(\alpha)^2 k_{eq} \quad (X)$$

where α is the slope with respect to the horizontal line of the struts (Figure 6). The equivalent period of the system is therefore given by:

$$T_{eq} = 2\pi \sqrt{\frac{m}{k_{eq}^*}} \quad (XI)$$

[0021] The steps of the proposed procedure are the following:

- (i) the SMA wires initial length L_0 is fixed;
- (ii) the maximum oscillation amplitude of the device is determined $\Delta u (= u_f - u_0)$, assuming to utilize the whole available superelastic strain range ($\varepsilon^{AM.f.} - \varepsilon^{MA.f.}$);
- (iii) the equivalent stiffness and damping (k_{eq}, ξ_{eq}) of the device at the calculated oscillation amplitude Δu (see Figure 7) are evaluated;
- (iv) the equivalent period is calculated through relationship (XI);
- (v) through a spectral analysis the device maximum displacement u_f^* , produced by the design earthquake, is derived;
- (vi) the value of the displacement u_f^* is compared with the one of u_f assumed at the step (ii): if the two values coincide, the procedure is concluded, else the passes from (ii) to (iv) will be repeated modifying u_f until convergence.

[0022] If the final. displacement is higher (lower) than the transformation finishing displacement u^{AMf} (u^{MAf}) (see Figure 7) then it is necessary to repeat the procedure increasing the wires Length L_0 . The optimal length is the one for which the displacement u_f^* coincides with the displacement u^{AMf} , that is $u_f^* - 2\Delta u$ with u^{MAf} . The above described procedure must be performed considering both the temperature $T_{med.max}^*$ and the temperature $T_{med.min}^*$ since it is not possible to a priori establish which is the heaviest temperature condition in case of earthquake.

[0023] As said before, the effectiveness of the length evaluated in this way through relationships proposed both in. serviceability (thermal effects) and seismic conditions, must be verified through proper numeric models to simulate more accurately the effects that can. be produced in both cases.

[0024] In serviceability conditions, the thermal and mechanical behavior of the system "SMA + steel chain" can be described with an iterative procedure able to follow kinetics of the martensitic phase transformation, assuring (step after step at the temperature changing) the satisfying of equilibrium and congruence conditions that involve SMA wires and steel chain.

[0025] The numeric model adopted for seismic analysis, instead, is based on the combination in parallel of elementary rheological models that can be simply integrated into a finite elements code. The numeric analyses are carried out with step by step integration, modeling the seismic action through a set of accelerograms compatible with the vertical component of the response spectrum of the place where the device has to be used. The earthquake horizontal components do not generally represent a problem for the arch itself but for the piers, which have often not negligible mass. On the other hand, in presence of sufficiently robust piers or of counterforts, the arch/vault structures exhibit high strength towards seismic horizontal components, with collapse PGA clearly higher than the maximum one of the expected earthquakes in Italy and Europe. The real problem is so represented by the seismic vertical component which has as effect to change the horizontal thrust exerted by the arch, producing often significant increases in terms of maximum flexure and shear stresses induced on the horizontal structures that bear the arch or the vault. The design force and displacement of the device are represented by the mean values of the more onerous effects obtained from the analyses, if at least 7 different groups of accelerograms are used, by the most onerous effects values, in the contrary case.

[0026] Generally, to further enhance the thermal behavior of the system with the SMA device, is necessary to adopt a SMA material with reduced hysteresis. In this way, in fact, when, after a temperature increase, the SMA wires shorten, the plateau of the inverse phase transformation is reached before, limiting so drastically the further variations of force. Opposite, the use of wires with reduced hysteresis penalizes the device dissipative capacity in presence of earthquake, with subsequent increase of the displacement request. The choice of the optimal SMA material, so, must derive from a proper arrangement between the device effectiveness toward both thermal ranges and seismic actions. Finally it is important to underline that the parameters most influencing the material hysteresis are, from one hand, the alloy composition and its initial treatment, on the other, the training which the SMA wires have been subjected to before their installation in the device. Operating on the above mentioned parameters it is possible, at least in theory, to select the hysteresis level most suitable for the different design conditions that may be really faced.

Claims

1. System applicable in building industry to thrusting structures including at least one device (1) based on shape

memory alloys (or SMA), at least a metal chain (6) and at least an anchor plate (7), **characterized by** the fact that the stress changing in the chain (6), caused by variation of the room temperature or by seismic phenomena, are limited and controlled by the thermal and mechanical behavior of the mentioned SMA device (1), which results to be antagonist with respect to the chain one (6).

2. System applicable in building industry to thrusting structures according to claim 1, **characterized by** the fact that said. device (1) is assembled in series to the steel chain (6), anchored itself to its own anchor plate (7).
3. System applicable in building industry to thrusting structures according to claims 1 and 2, **characterized by** the fact that the mentioned device (1) based on shape memory alloys SMA is constituted by several superelastic pre-stretched SMA wires (4), several means for anchoring (2) and pre-stretching (5) said superelastic wires (4).
4. System applicable in building industry to thrusting structures according to claims from 1 to 3, **characterized by** the fact that said SMA superelastic wires (4) are accommodated in a wire case (3).
5. System applicable in building industry to thrusting structures according to claims from 1 to 4, **characterized by** the fact that the chain (6) stretching operation is carried out pre-stretching the SMA wires (4) when the chain (6) and the devices (1) are already assembled and fixed to the anchor plate (7).
6. Procedure for the dimensioning and the implementation of the SMA device (1) integrated in the system according to the claims from 1 to 5, **characterized by** the following phases:

(i) the SMA wires number (n_{SMA}) needed for adsorbing the horizontal thrust (H) transmitted by the arch must be evaluated through the relationship (I)

$$n_{SMA} = \frac{H}{\frac{\phi_{SMA}^2}{4} \cdot \pi \cdot \sigma_{SMA}^0}$$

(ii) the minimum SMA wires length ($L_{SMA,min}$) in serviceability conditions, is given by the relationship (VI)

$$L_{SMA,min} = \frac{L \cdot \alpha \cdot |\Delta T|}{\Delta \varepsilon_{SMA,max} + \alpha \cdot |\Delta T|}$$

(iii) the force variation (ΔF) of the system constituted by the metal chain (6) and the SMA device (1) is given by the relationship (VIII)

$$\Delta F = \Delta \sigma_{SMA} \cdot A_{SMA}$$

7. Procedure for calculating the SMA wires (4) length in case of earthquake of the SMA device (1) integrated in the system according to the claims from 1 to 5, **characterized by** an iterative procedure referring to a simplified arch model. that simulates the equivalent stiffness (k_{eq}) of the series between chain (6) and SMA based device (1) including the following steps:

- (i) the SMA wires initial length L_0 is fixed;
- (ii) the maximum oscillation amplitude of the device is determined Δu ($= u_f - u_0$), assuming to utilize the whose available superelastic strain range ($\varepsilon_{AM,f} - \varepsilon_{MA,f}$);
- (iii) the equivalent stiffness and damping (k_{eq} , ξ_{eq}) of the device at the calculated oscillation amplitude Δu (see

Figure 7) are evaluated;

(iv) the equivalent period is calculated through relationship (XI);

$$T_{eq} = 2\pi \sqrt{\frac{m}{k_{eq}^*}}$$

(vii) through a spectral analysis the device maximum displacement u_f^* , produced by the design earthquake, is derived;

(viii) the value of the displacement u_f^* is compared with the one of u_f assumed at the step (ii): if the two values coincide, the procedure is concluded, else the passes from (ii) to (iv) will be repeated modifying u_f until convergence.

8. System applicable in building industry to thrusting structures according to one of the previous claims 6 or 7, **characterized by** the fact that the SMA wire length evaluated according to the described procedures must be verified through proper non linear numeric models to simulate more accurately the thermal and mechanical behavior of the material in both design conditions.

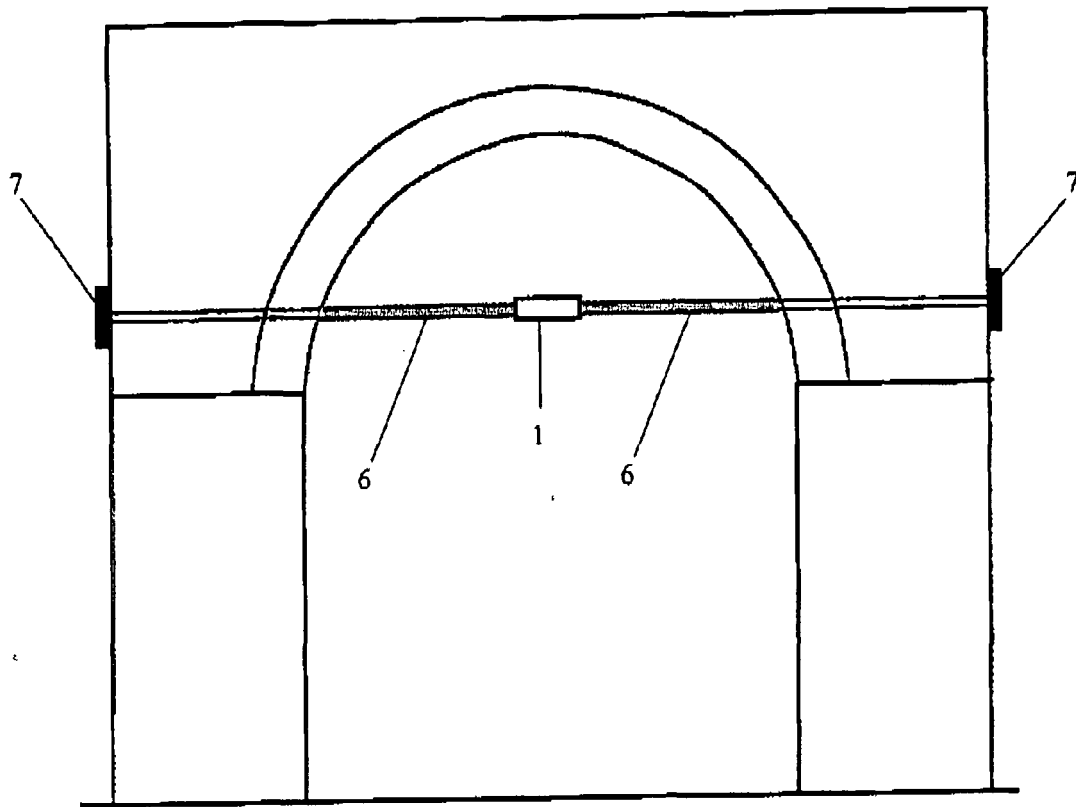


Figure 1

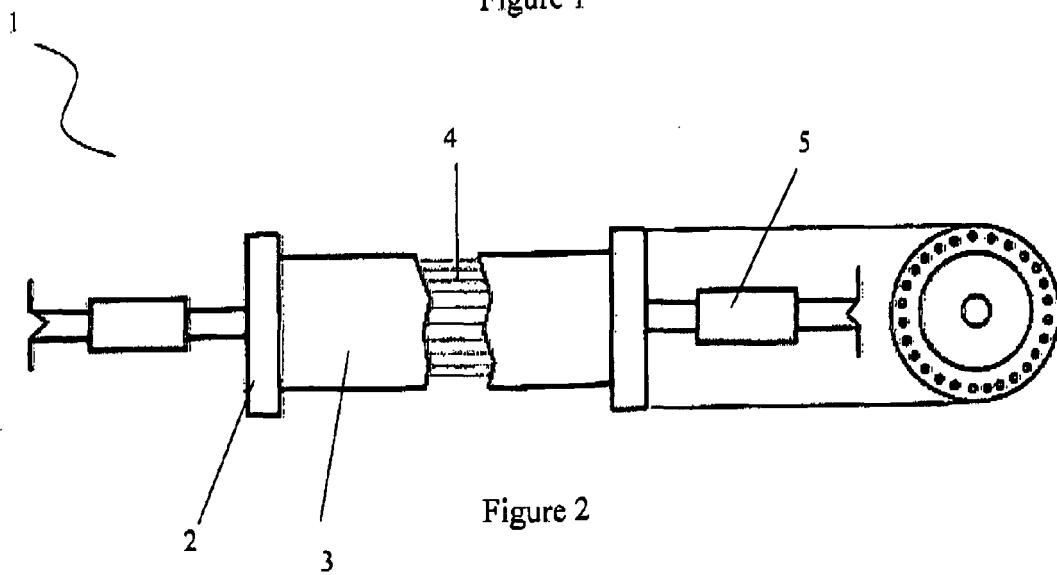


Figure 2

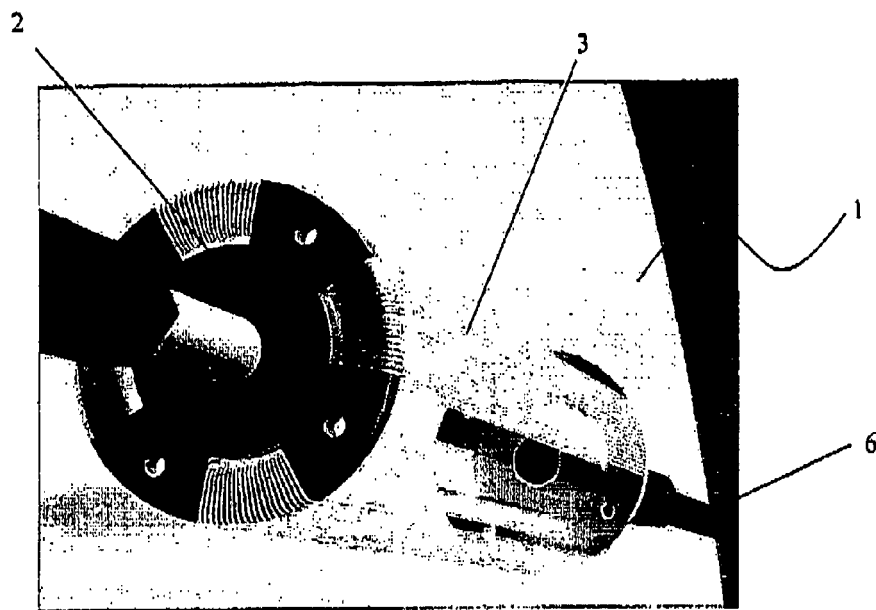


Figure 3

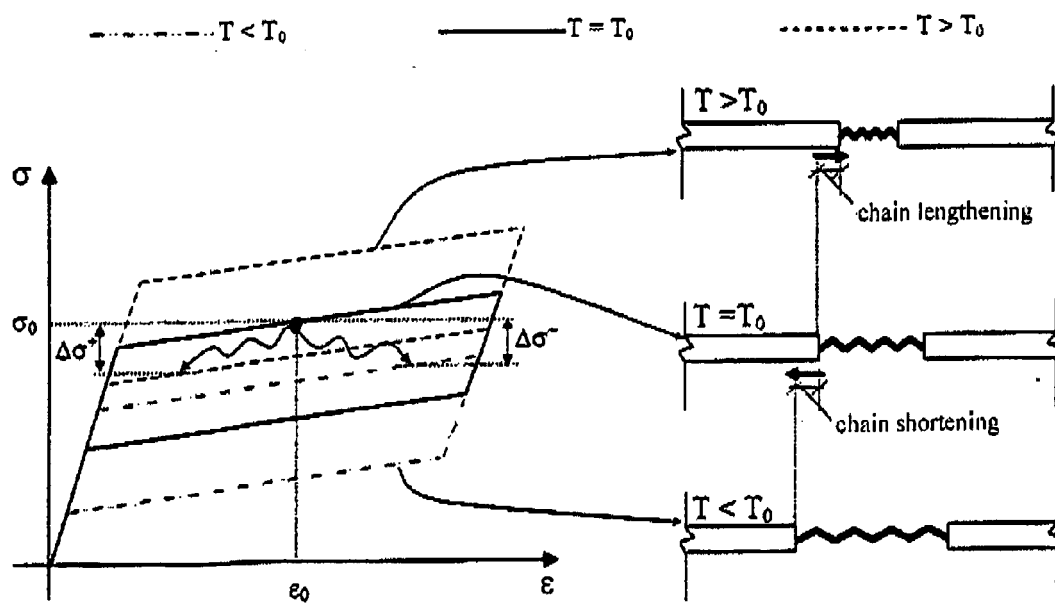


Figure 4

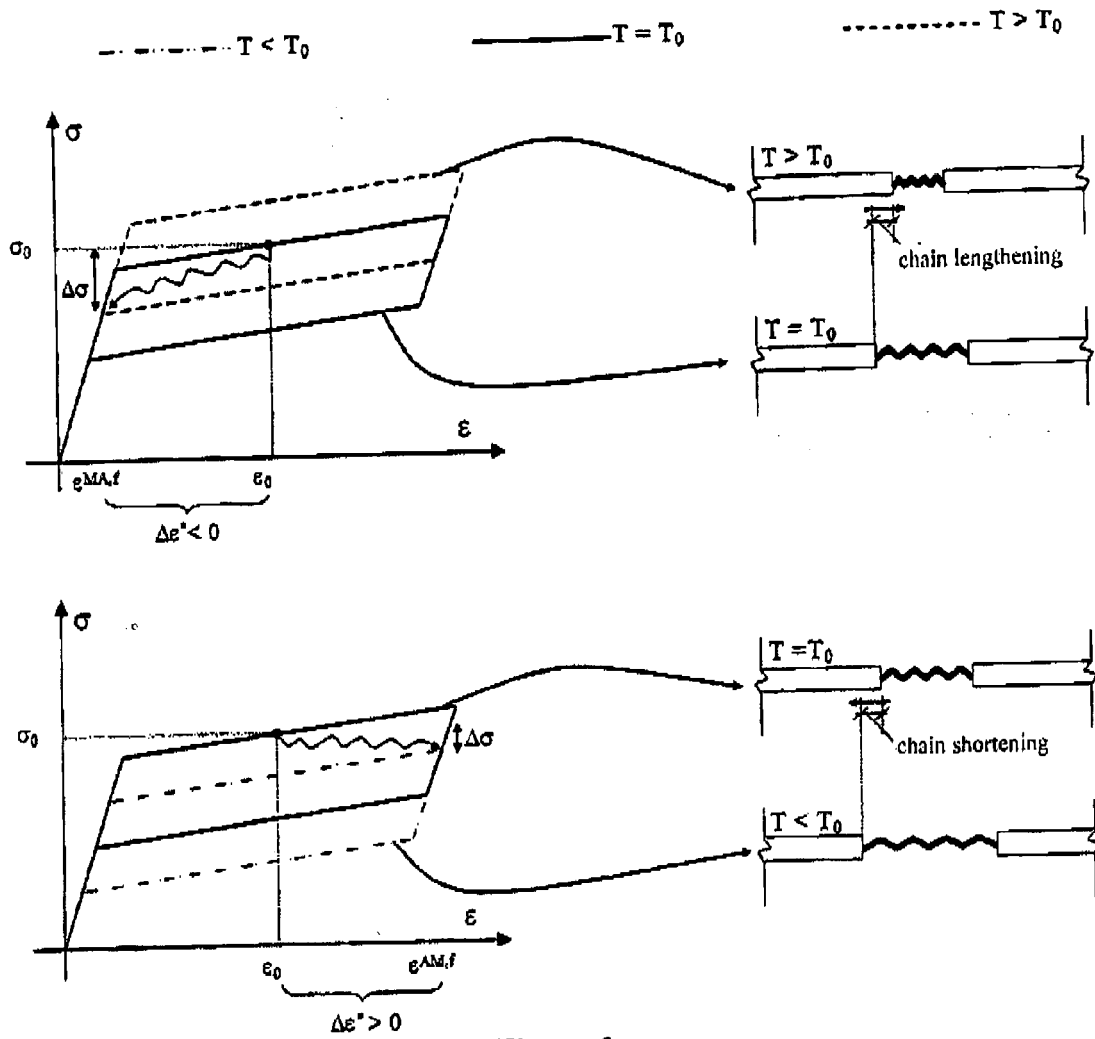


Figure 5

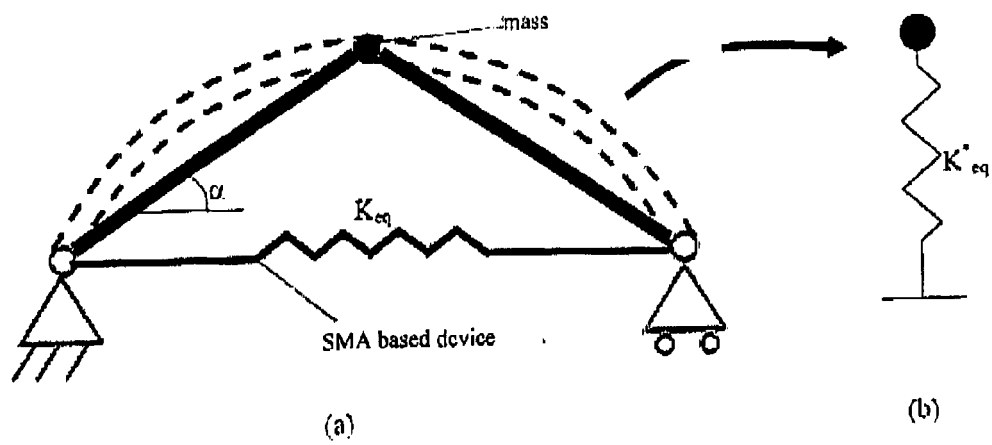


Figure 6

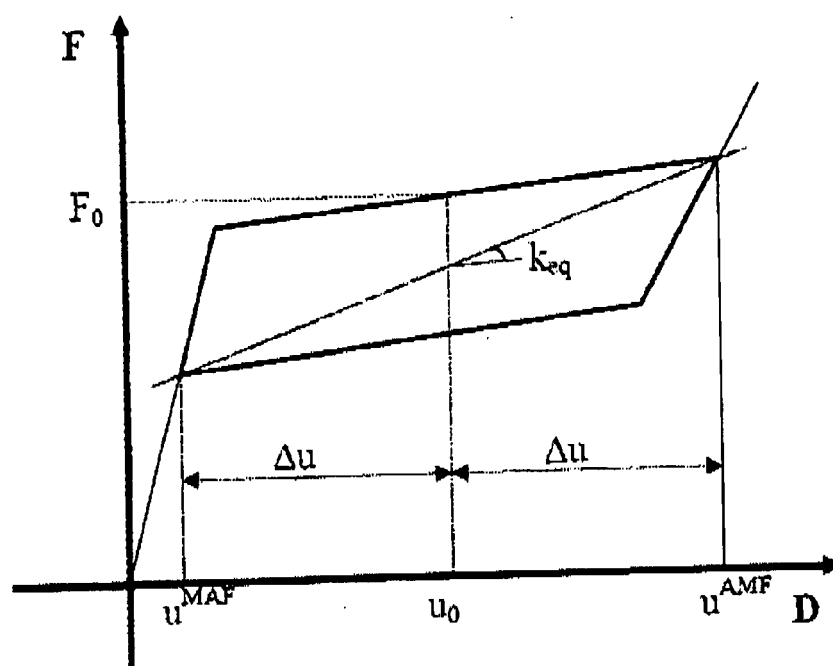


Figure 7

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

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