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Passive control of structures – the dynamic case

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Passive control of structures

Abstract. Lately, powerful earthquakes stroke some parts of the world, while the Balkan peninsula was hit by moderate ones. During a powerful earthquake, a building structure is invaded by an enormous quantity of kinetic energy E_K. From the manner this energy is first absorbed, then dissipated throughout building structure depends, not only the reaction of structure, or structural elements in particular, but the nature, the distribution and the quantity of the damages also. As Nikola Tesla once quoted: "If you want to find the secrets of universe, think in terms of energy, frequency and vibration". In order to be able to achieve some degree of control, in structural engineering, the frequency is the fundamental parameter one must begin with. Passive control is actively implemented in the developed countries, whereas intensive laboratory examinations are underway the last two decades in the domain of semi-active and active structural control as well. This Paper, as a first deals with the static case, i.e. the behavior of a simple cantilever structure, treating its sensitivity towards shear and bending.

Keywords: Structural control, Energy, Base isolation, Seismic isolation

1 Introduction

When Nikola Tesla quoted: "*If you want to find the secrets of universe, think in terms of energy, frequency and vibration*", it is most certain he should have had more important things in his enlightened mind than the manner an engineering structure behaves when submitted to external actions, and yet, it is so meaningful for someone willing to understand how a structure behaves in this situation.

During the last hundred years and until today the design approach is the one based on strength of a structural element particularly or the whole structure. Nowadays, at the very heart of each of modern codes lies the design based on the interplay between the strength and ductility. Put simply: the ductility demand (*DD*) must be overcome by the ductility supply (*DS*), be it at the local or the global level.

Force-based methods, or as they will be called hereafter - conventional design methods or approach - impose as the basic requirement, that the structure responds passively to the hazards (earthquake, wind, etc.), mainly through the combination of resistance, on the one side, and deformability, energy absorption and dissipation, on the other. It is already well established that, during a strong earthquake, the structure undergoes significant deformation (and therefore damage) and, nevertheless, "survives" thanks to its inelastic "excursion" [1].

The designer, therefore, finds himself in situation where he/she has to choose between a strong structure, responding into the linear-elastic domain, i.e. suffering small if any deformations/damages at all, or, a weak one – undergoing important deformations/damages once the hazard has gone. The former requires big expenditures on primary lateral load resisting members, whilst the flexible one is economically much more suitable if built in such a way as to resist to moderate (frequent) hazards.

But what about a structure responding within velocity sensitive natural periods? Actual behavior of structures during strong earthquakes or winds has shown that neither of the design approaches mentioned above is enough in order to guarantee a satisfactory behavior – a new and modern approach, based on stiffness deployment is necessary.

This paper in all its modesty aims to treat the subject of the so called "motion based" design. The approach uses some of fundamental mechanical principles in order to first absorb and afterwards dissipate a good part of the energy input imposed to a structure, fulfilling thereof two of the principal requirements: Collapse prevention and serviceability (normal use) including users comfort level.

Problem definition - conceptual design, creative phase and finally problem refining or carving is directly connected with human activity [2], whilst machine interaction can help the above-mentioned activities, but can never replace them.

This paper is a modest attempt to increase the awareness in relation to the nonconventional approach when undertaking the structural design of highly sensible civil engineering structures, namely high-rise buildings.

1.1 Human response and sensitivity to vibrations

Whereas conventional design of structures tailors its members based on strength requirements, establishes the relevant stiffness properties and only then checks the serviceability criteria (SLS – EN 1990), while maintaining the strength as the principal requirement (ULS), the ever increasing trend of designing flexible structures, shifts the emphasis towards displacement (motion) based design.

Frequently, some facilities, such as hospitals, data storage centers, etc., must remain operational even after they undergone a strong earthquake. Another example could be semi-conductor manufacturing center, where hypersensitive equipment must stay (almost) motion-free, since its monetary value may sometimes even exceed that of the building itself. On the other hand, comfort limits for humans are somewhere near $0.02g$ in terms of building accelerations. The parameters affecting human sensitivity to vibrations are enlisted excellently in [1 – Bachmann, 1997], whilst the Codes treating the subject are [ISO 2631] and [DIN 4150]. As an example, the human perceptibility threshold (person standing) for vertical harmonic vibrations is $34\,mm/s^2$ – just perceptible, to $1800\,mm/s^2$ – intolerable.

While sight or hearing are two sensory phenomena centered on two of the basic organs of the human body, oscillation receptors are like those of heat / cold and are in some degree a continuation of the nervous system. Thus, the human finger has receptors with such a degree of sensitivity, that it can probe oscillations whose amplitude revolves around values of $1 \cdot 1^{-3}\,mm\ to\ {}^{1}\!/_{20} \cdot 10^{-3}$ [1].

When a person works within a shaking skyscraper, he feels uncomfortable on a scale that can range from "barely sensitive" to "intolerable" one. The degree of comfortability depends a lot on user's location, as he will not feel the same when sitting in his office on the $52nd$ floor of a New York skyscraper or on the second floor of a restaurant in Berlin at an event organized by his friends.

Among the basic parameters that affect human susceptibility to oscillations are [3]: position (standing, sitting, lying down), direction of incidence with respect to the spine, personal activity (at rest, walking, running), sharing the activity with others, age and gender, frequency of occurrence and time of day, the character of the weakening (extinction) of the oscillations, etc., whilst the intensity of perception depends on displacement, velocity and acceleration amplitudes, duration and frequency of vibrations [3].

As for the *criteria* related to the intensity of perception [3] (sensitivity), they are expressed through a single parameter which is the *effective acceleration* (rms - Root Mean Square) and is given by expression (1.1) as follows:

$$a_{eff} = \left(\left({}^{1}\!/_{T}\right) \cdot \int_0^T a^2(t)dt\right)^{{}^{1}\!/_{2}} \qquad (1.1),$$

Where T – is the time period within which effective acceleration has been measured.

ISO 2631, distinguishes three different levels of human inconvenience (comfortability) to vibrations:

— *The reduced comfort limit*, which is the threshold at which human activities such as eating, reading or writing are hampered by vibrations.

— *The fatigue-decreased proficiency boundary*, which refers to the threshold where repeated oscillations cause fatigue in (working) staff, with a direct (negative) result in reduced productivity. In intensity, this threshold corresponds to three times the limit of reduced comfort.

— The *exposure limit* is the upper limit of oscillation tolerance for the health and safety of the individual. This limit corresponds to six times the limit of reduced comfort.

1.2 Additional Information Required by the Volume Editor

2 Sensitivity of a cantilever structure depending on type of action - shear load or bending moment

From classical beam bending theory [4], the differential equation governing the beam deflections is given by equation (2.1) below:

$$z'' = -\frac{M}{EI} \qquad (2.1)$$

Where: z – vertical deflection; M – bending moment; E – elasticity modulus; I – moment of inertia of the beam cross section. In the case of a cantilevered beam (see figure below), deflections are given by the expression (2.2) [4],

$$z = z_M + z_T \qquad (2.2)$$

Where the displacement due to bending moments is given by expression (2.2a),

$$z_M = \frac{P}{EI} \cdot \left(\frac{l}{2} - \frac{x}{6}\right) \cdot x^2 \qquad (2.2a)$$

Whilst the deflection due to the transversal (shear) loads is given by expression (2.2b),

$$z_T = \frac{P \cdot l}{GF} \cdot \alpha \qquad (2.2b),$$

where: α – coefficient depending on the shape of cross-section; G – shear modulus; and, F – cross-section area of the beam.

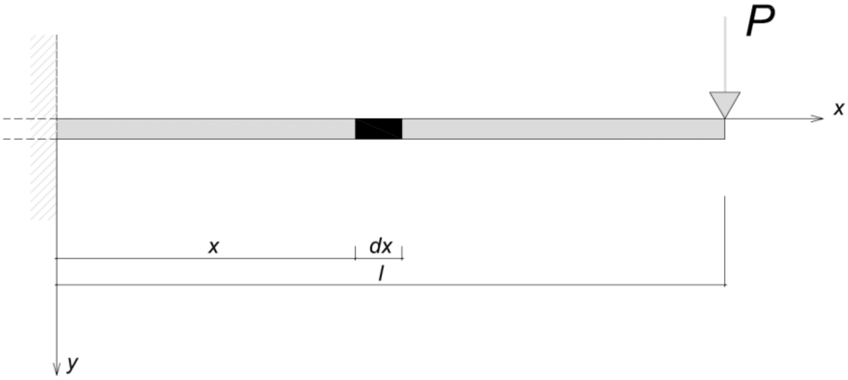
$Fig. 2.1$ Cantilevered beam submitted to a concentric load P

Timoshenko [4], gave an expression (2.3), which is like (2.2),

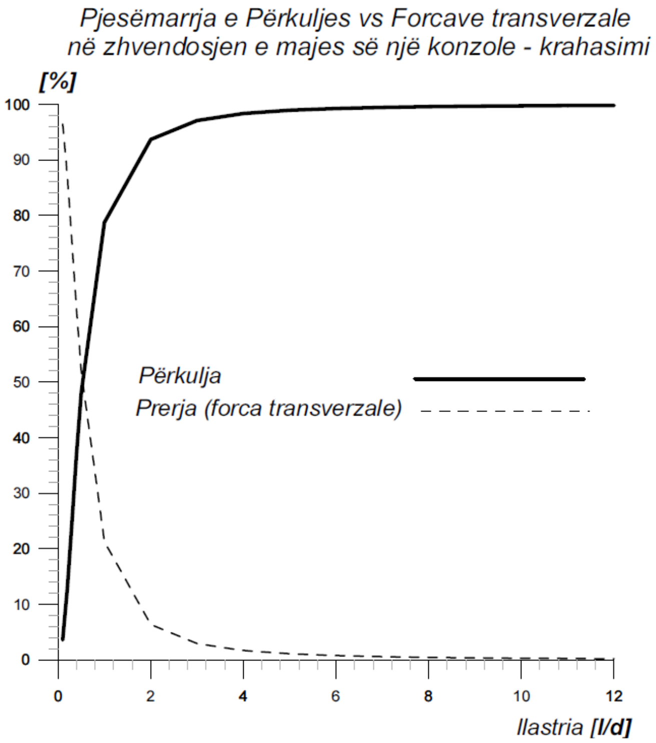
$$z = \frac{P\cdot l^3}{3EI}\cdot\left(1+0.98\cdot\left(\frac{d}{l}\right)^2\right) \tag{2.3}$$

Where: d/l – represents the slenderness ratio of the beam.

Based on any of fundamental principle of mechanics, one can easily derive the expression for bending or shear stiffness of the beam (expressions 2.4), meanwhile, the fig. 2.2 below shows both bending and shear stiffness in function of beam's slenderness ratio d/l. It is worthy to remark, that for a slenderness of $d/l \sim 1.02$, the share between relative participation is 50 % approximately.



$$\begin{cases} k_{\text{përkulje}} = 3EI/l^3 \\ k_{prerje} = EF/3l \end{cases} \tag{2.4}$$



$Fig.2.2$ Percentage of participation of shear and bending on deflection for the cantilevered beam shown in $Fig.1$

It is clear, from the Fig 2.2 above, the degree of shear-stiffness "mobilization" towards deflection participation is from *low,* for flexible structures (high slenderness ratio, participation ratio $\sim max$ 4%) to *very low*, for "bulky" structures (low slenderness ratio $\sim$0%). This speaks a lot about the degree of sensitivity of a structure, when the slenderness is taken as a comparative measure.

3 Static effect cantilever beam with high bending stiffness (elevated sensitivity towards the effect of shear loads)

Let us consider, once again, the cantilevered structure in Fig 1 above, but rotated anticlockwise for 90 degrees now, submitted to a horizontal load P.
Shear stress due to the above loading conditions is given by expression (3.1) below,

$$\tau_{pr} = {}^{P}\!/_{F_{pr}} \tag{3.1}$$

Where: F_{pr} – represents the area cross section of the beam within which shear stresses are assumed to be constant (the distribution is parabolic!)
In order to comply with the *resistance design criteria* (*ULS*) of the cross section, the necessary cross-sectional area of the beam must fulfil the requirement according to the expression (3.2) below,

$$F_{pr}^{rezist} \geq {}^{P}\!/_{\tau_{pr}^{lej}} \tag{3.2}$$

Where: τ_{pr}^{lej} - is the admissible shear stress for the selected material.

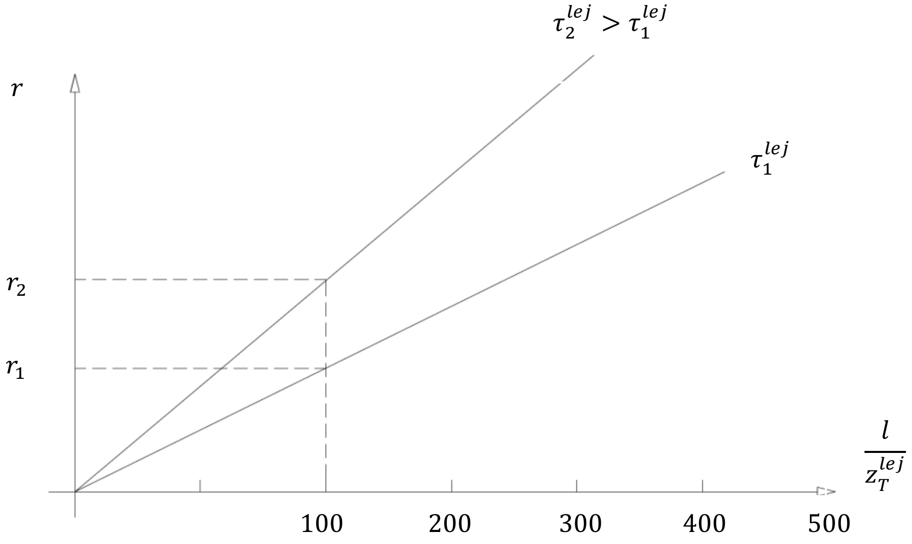
In the same way, the necessary cross-sectional area of the beam in order to comply with *admissible deflections criteria (SLS - serviceability)*, must fulfil the requirement according to the expression (3.3) below,

$$F_{pr}^{shfrytzueshm.} \geq \frac{P}{G} \cdot \frac{l}{z_T^{lej}} \tag{3.3}$$

Where: z_T^{lej} – represents the admissible (acceptable) displacement of the tip of the cantilevered structure – normally given in advance, in accordance with user's comfort [3].
Let now build the ratio between the two cross-sectional areas given by expressions (3.2) and (3.3), see expression (3.4) below,

$$\boldsymbol{r}_1 = \frac{F_{pr}^{shfrytzueshm.}}{F_{pr}^{rezist}} = \frac{\tau_{pr}^{lej}}{G} \cdot \frac{l}{z_T^{lej}} \tag{3.4}$$

The ratio $\boldsymbol{r}_1$ represents the threshold which underlines the relative importance of the *displacement design constrains* versus resistance *(strength) design constrains.* The Fig 3 below shows the relation between $\boldsymbol{r}_1$ and l/z_T^{lej}, for given values of $\tau_{pr}^{lej}\ /G$, which is constant for a selected material (e.g. steel $S235$). Therefore, the ratio $\boldsymbol{r}_1$ grows linearly, so for decreased values of allowed deflections z_T^{lej} it grows continuously and thus it puts added emphasis over displacements (on motions).
Also, from the equation (3.4), we can see that if we attempt to "intervene" in the quality of the material, it is clear the ratio $\boldsymbol{r}_1$ increases ($r_2 > r_1$), which practically means yet more sensitivity (increase of structural sensitivity).



$Fig.$ 3.1 Graphical presentation of sensitivity $\boldsymbol{r}$, for the cantilevered structure in function of its slenderness l/z_T^{lej}

Starting from the beginning of the 20th century, and then continuing into the forties until its end, the technology of materials used in civil engineering has been under a linear increase - both in production procedures, increasing their quality, and especially their mechanical resistance refinement. It is particularly noteworthy, that while the mechanical resistance (e.g. concrete or steel) has been doubled, at least, if not quadrupled in some cases, their material stiffness (corresponding modulus of elasticity) has remained almost constant [2].

4 Static effect cantilever bending beam with low shear bending (elevated sensitivity towards the effect of bending loads)

Let analyze once again the cantilevered structure as shown in Fig 2.1. The bending moment at cantilever's spring (the fixed support) is

$$M = -P \cdot l \tag{4.1}$$

The bending stress σ is a well-known expression from the Strength of materials

$$\sigma_{p\ddot{e}rk} = {}^{M}\!/_{I_{pr}} \cdot z \qquad (4.2),$$

Or, if expressed in terms of section modulus $W_{p\ddot{e}r}$

$$\sigma_{p\ddot{e}rk} = {}^{M}\!/_{W_{p\ddot{e}r}} \qquad (4.3),$$

Where: I_{pr}- is the moment of inertia of the cross-section, z – is the fiber's distance from the neutral axis, $W_{p\ddot{e}r} = I_{pr}/\left({}^{d}\!/_{2}\right)$ – is the section modulus

The displacement at the tip of the cantilever, under the actual load is

$$u_{p\ddot{e}rk} = {}^{P \cdot l^3}\!/_{3EI_{pr}} \qquad (4.4),$$

In order to comply with the *resistance design criteria* (*ULS*) of the cross section, the necessary cross-sectional moment of inertia of the beam must fulfil the requirement according to the expression (4.4) below,

$$I_{p\ddot{e}rk}^{rezist} \geq {}^{P \cdot l \cdot d}\!/_{2\sigma_{p\ddot{e}rk}^{lej}} \tag{4.4}$$

Where: $\sigma_{p\ddot{e}rk}^{lej}$ - is the admissible bending stress for the selected material.

In the same way, the necessary moment of inertia of the beam in order to comply with *admissible deflections criteria (SLS - serviceability)*, must fulfil the requirement according to the expression (4.5) below,

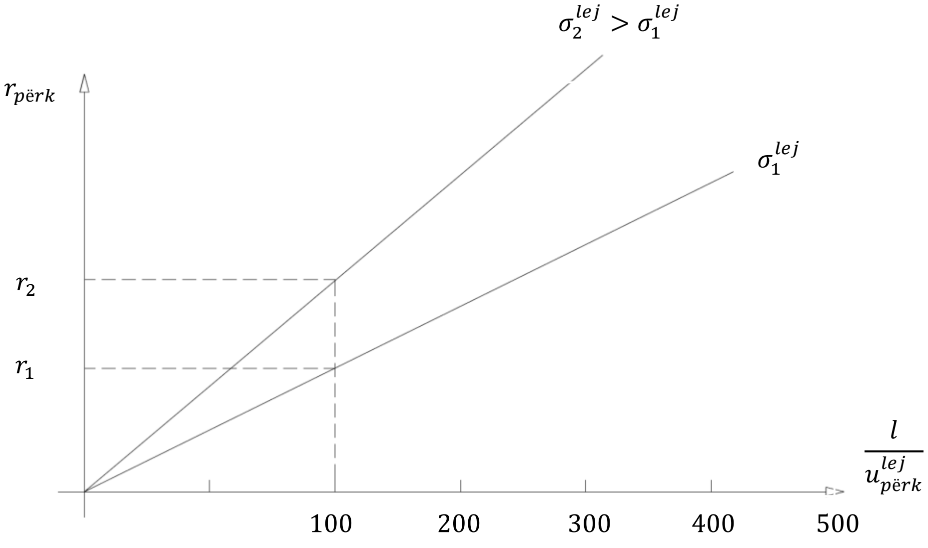
$$I_{p\ddot{e}rk}^{shfrytzueshm.} \geq {}^{P \cdot l^3}\!/_{3Eu_{p\ddot{e}rk}^{lej}} \tag{4.5}$$

Where: $u_{p\ddot{e}rk}^{lej}$ – represents the admissible (acceptable) displacement of the cantilever's tip.

Once again, we establish the ratio between the moment of inertia required to satisfy *serviceability criteria* to the moment of inertia required to satisfy *strength criteria*

$$r_{p\ddot{e}rk} = \frac{I_{p\ddot{e}rk}^{shfrytzueshm.}}{I_{p\ddot{e}rk}^{rezist}} = \frac{P \cdot l^3}{3Eu_{p\ddot{e}rk}^{lej}} \cdot \frac{2\sigma_{p\ddot{e}rk}^{lej}}{P \cdot l \cdot d} = \frac{2l}{3d} \cdot \frac{\sigma_{p\ddot{e}rk}^{lej}}{E} \cdot \frac{l}{u_{p\ddot{e}rk}^{lej}} \tag{4.6}$$

Like the Fig 3.1, the plot below shows the dependence of the ratio $r_{\text{përk}}$ in function to mainly three parameters: *global slenderness* $\frac{l}{d}$, *allowable deformations* $\frac{\sigma_{\text{përk}}^{lej}}{E}$, and finally the ratio of the beam's span l to allowable tip displacement $u_{\text{përk}}^{lej}$.



$Fig.$ 4.1 Graphical presentation of sensitivity parameter $\boldsymbol{r}$, for the cantilevered structure in function of its slenderness $l/u_{\text{përk}}^{lej}$

Like in the case of the shear beam, each increase of $l/u_{\text{përk}}^{lej}$, i.e. the decrease of the allowable displacement $u_{\text{përk}}^{lej}$, puts more emphasis on displacement if span is to l remain constant. One could increase the allowable bending stress (steel grade or concrete class), hoping to decrease the (overall) sensitivity, but $\sigma_{\text{përk}}^{lej}$ puts even more emphasis on *displacement constraint*, as it is shown in the $Fig.$ 4.1 above.
For example, let consider a steel beam of strength class $S235$, with allowable stress (yield strength) $f_{y,k} = 200\,N/mm^2$ [5], a Young's modulus $E = 170000\,N/mm^2$, and a slenderness $l/d = 8$. The value $l/u_{\text{përk}}^{lej}$ at which (the sensitivity) a transition from strength to serviceability occurs can easily be calculated from expression (4.6) ($r_{\text{përk}} = 1$),

$$\left.\frac{l}{u_{\text{përk}}^{lej}}\right|_{r_{\text{përk}}=1} = \frac{3}{2}\cdot\frac{d}{l}\cdot\frac{E}{\sigma_{\text{përk}}^{lej}} = \frac{3}{2}\cdot 8^{-1}\cdot\frac{170000\,N/mm^2}{200\,N/mm^2} = \sim 160$$

Thus, for $\frac{l}{u_{\text{përk}}^{lej}} > 160$, i.e. $r_{\text{përk}} > 1$, the structural design of the cantilevered structure is governed by its tip displacements.
Let now try to improve the steel grade and instead of $S235$ we use steel $S355$, with $f_{y,k} = 355\,N/mm^2$, whilst Young modulus and slenderness remains unchanged, $\left.\frac{l}{u_{\text{përk}}^{lej}}\right|_{r_{\text{përk}}=1} = \frac{3}{2}\cdot\frac{d}{l}\cdot\frac{E}{\sigma_{\text{përk}}^{lej}} = \frac{3}{2}\cdot 8^{-1}\cdot\frac{170000 N/mm^2}{355 N/mm^2} = \sim 90$, so it is evident now, that displacement controls the Design process, for the full range of the admissible displacements $u_{\text{përk}}^{lej}$.

5 Summary

The last decades, many research studies have been going on relating to the Design approach. Currently, most structural codes worldwide have adopted the approach based on force as a design strategy, i.e., an approach based on giving the necessary strength/ductility to the structural elements, or to the whole structure in general.

Now, in a philosophical point of view – does it exist an objective reason of the force to exist, and how do we cognitively recognize it? It is a generalized displacement of a node, that makes us knowledgeable of the force existence, that is, because of the fact we see the displacement, we are certain of the force existence. It is precisely this fact, although known since the dawn of engineering, that during the last three decades initialized the displacement design approach thinking within the professional community, first in USA, and afterwards elsewhere in industrialized countries.

Human being does possess a sensitivity towards external natural phenomena in general, and vibrations in particular. Thus, acceleration of the order 0.02g are the threshold at which humans begin to feel uncomfortable [Eurocode 8]. On the other hand, structures, in dependence of their physical characteristics, do possess a certain level of sensitivity. A structural designer, when has several possibilities at his disposal: to design a strong structure, that is, a structure responding quasi statically; a structure designed in the domain of resistance/ductility response; a flexible to very a flexible structure, responding within the increased displacements domain. The first family of structures requires higher initial costs, the second one can be economical, whilst the last family can be built with medium to low initial costs but can suffer important to very high damages after it has been submitted to externa hazards.

In this first paper, hoping to be continued with yet another one, the Author has attempted in a modest yet significant manner to underline the importance of structural sensitivity, first for a shear beam and second for a bending beam. For the first family of structures the importance of shear stresses and their contribution to the total amount of displacement has been treated, based on Timoshenko's classical beam theory [Timoshenko], whilst in the second case, the bending stress importance for the same parameter has been analyzed. Both for the first as well as for the second case sensitivity parameter $\boldsymbol{r}$ [6] has been represented graphically, in order to underline the importance of *serviceability criteria* towards the *strength* (resistance) *criteria*.

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