THE EFFECT OF STRUCTURAL DEGRADATION ON THE DYNAMIC BEHAVIOUR OF BUILDINGS

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Abstract: The paper is an analysis of buildings behavior during strong earthquakes, considering the modifications of the structural dynamic characteristics due to strong earthquake - generated damages. The study is focused on the difference in a building behavior, function of the mode the structure is situated relative to the seismic ground motion from the spectral point of view: below resonance or above resonance. Experimental and simulation results are presented for simplified mechanical models of building structures with stiffness degradation. As a convenient measure of the effect of duration and severity of the building seismic loads, the total energy dissipated through hysteresis is considered.

Key-Words: buildings, structural degradation, strong earthquake motion, hysteresis

1 INTRODUCTION
The acceptance of plastic hinges occurrence in a building, according to the seismic design standards [1-3], leads to a degradation of the structural restoring force and to an increase of the structural damping. The first effect could be beneficial if the natural vibration frequencies of the building are lower than those of the main spectral components of the ground motion ("fast earthquakes"). In this case, by structural stiffness degradation the building is "pulled" from the resonance regime resulting in a reduction of seismic response. On the other hand, if the main spectral components of the seismic ground motion have frequencies lower than the building natural frequencies ("slow earthquakes"), then the structure could be “dragged” to resonance with a significant increase of the seismic response, which can result in important building damages or even in collapse. The increase of the building structural damping capacity due to the occurrence of plastic hinges is beneficial in both cases as more of the kinetic energy injected to the building by the seismic action is consumed as the structure experiences repeated stress reversals. However, this increase of structural damping is not so important such as to dramatically reduce the vibration amplification within the resonance range. The dynamic behavior of buildings during an earthquake must be analyzed for both undamaged and damaged conditions of the building

2 EXPERIMENTAL ANALYSIS
To illustrate the change of dynamic behaviour of a structure, due to system degradation, an experiment was conducted on a simple mechanical structure. A cantilever beam from composite material with a concentrated mass on top (acceleration transducer) was mounted vertically on an electro-dynamic shaker.

From practical point of view, this experimental study is relevant when the beam vibrates in the neighborhood of the first resonant vibration mode because in this case the dynamic structural output is strongly amplified by favored transfer of the kinetic energy from the base imposed motion to the structure and damaging shear forces can develop. The accelerations of the clamped base and of the beam top were simultaneously recorded on a PC oscilloscope for both forced and free vibrations. The structural degradation was produced by gradual delamination of the composite material, resulting in a decrease of bending stiffness and a corresponding increase of internal damping. The frequency of the first bending vibration mode, denoted by $f_{1s}$, and the associated modal damping ratio, $\zeta$, were obtained from the free vibration records. Fig.1 presents the experimental results, showing the effect of structural degradation on the amplification factor A (defined as the ratio of the r.m.s values of the top and base acceleration).
During this test, the r.m.s value of the input acceleration and its fundamental frequency component were maintained practically constant \( a_{rms} = 0.64g, f_{in} = 3Hz \) and the initial frequency of the first vibration mode was higher than the driving frequency. As one can observe from fig.1a,b,c, below resonance \( f_{str} \geq f_{in} \) the amplification factor increases dramatically with the gradual degradation of the beam stiffness due to fatigue cyclic stresses. This important increase of A was obtained despite of some appreciation of self-damping capacity of the composite material. It should be mentioned that the dramatic increase of vibration amplification factor for a rather modest decrease of the beam resonant frequency was obtained because the test had been conducted in the neighborhood of the resonance range where the variation of the amplification factor is very rapid. The decrease of amplification factor when the vibration regime is moving away from resonance is illustrated in fig.1d and e. The two different bending vibration patterns, which take place below and above resonance for almost same value of the amplification factor, are shown in fig1.b and d. It is easily seen that below resonance the base and top motions are almost in phase whereas above resonance these motions are almost 180\(^\circ\) out of phase. The gradual change of phase shift with beam degradation can be observed in fig.1a-e. For same amplification factor, above resonance both bending moment and shear force along the beam are bigger than below resonance. Moreover, above resonance the shear force has a maximum value at an almost fixed transversal section of the structure, which, for reasonable values of amplification factor, is located around one third of the beam length. Inspection of damaged buildings after major earthquakes reveals in many cases breakages of structural elements between second and third floor. A possible explanation of this damage pattern is discussed in [4]. Therefore, in some cases, the building response excited by the ground motion above resonance could be more damaging to the structural elements than below resonance.

### 3. ANALYTICAL MODEL

Although an multiple-storey building is envisaged, the model adopted employs only one mass, the aim being to approximate the building vibration in the range of its lowest mode. Only lateral motion is considered, the building being treated as a shear structure as shown in fig.2. The sprung mass, \( M \), is connected to the system base by an element of Kelvin-Voigt type, generating a hysteretic force, \( F(t) \), given by

\[
F(t) = ky(t) + c\dot{y}(t)
\]

(1)

where \( y(t) = x(t) - u(t) \) is the relative displacement between the top level and the building
Degradation of the restoring force gradually increases as the structure experiences repeated stress reversals. The degradation due to the occurrence of plastic hinges, leads to a certain increase of energy dissipation by the internal damping mechanism. The viscous damping force term in (1) is view as an equivalent damping of the internal energy dissipation. The parameters in any hysteretic model must become time dependent, if these degradation effects are to be accounted for. The degradation mechanism can be modeled by allowing the parameters $k$ and $c$ to vary as a function of the response duration and severity [5,6]. As convenient measure of the combined effect of duration and severity is the total energy dissipated through hysteresis over the time interval $[0,T]$. Taking into account that in the considered hysteretic model the energy dissipation is of viscous type, a simplified model of degradation can be expressed by the following linear functional relationships for the instantaneous values of the system relative damping coefficient, $\zeta(t)$, and natural undamped pulsation, $\omega(t)$, and natural undamped pulsation, $\omega(t)$, and natural undamped pulsation, $\omega(t)$, and natural undamped pulsation, $\omega(t)$,

$$\zeta(t) = \zeta_0 \left[ 1 + \alpha \int_0^t 2\zeta(\tau)\omega(\tau)\dot{\gamma}^2(\tau)\,d\tau \right],$$

$$\omega(t) = \omega_0 \left[ 1 - \beta \int_0^t 2\zeta(\tau)\omega(\tau)\dot{\gamma}^2(\tau)\,d\tau \right]$$

where $\zeta_0$ and $\omega_0$ are the initial values of the undamaged structure and $\alpha,\beta$ are non-negative parameters. The equation of motion of the system with degradation may be written as

$$\ddot{y} + 2\zeta(t)\omega(t)\dot{y} + \omega^2(t)y = -\ddot{u}$$

Combining the motion equation (3) with the degradation model (2), one obtains an integro-differential equation to portray the dynamic behaviour of a degrading oscillating system perturbed by the base acceleration, $\ddot{u}(t)$. In order to solve this problem one must assess the values of coefficients $\alpha$ and $\beta$, associated with the system degradation. Let us consider a cyclic loading with the amplitude $y_c = 0.15m$ and the frequency $f_c = 1Hz$. Assuming that after completion of 15 testing cycles (15 seconds) the system damping capacity increases two times while its stiffness decreases three times, yields $\alpha = 0.1s^2/m^2$ and $\beta = 0.2s^2/m^2$. From an intuitive point of view, this cyclic loading is fairly realistic if one thinks of building first vibration mode period and of the relative displacement between the building base and top level, which can occur during strong earthquakes. Large relative movements within a building (drift) are liable to fracture strengthening structural elements and may result in serious building damages or even in collapse. For this reason it is desirable to keep drift below 0.5% storey height [7]. Therefore, a total drift of 0.15m could be acceptable for a building height greater than 30m. On the other hand, the limitation of drift by introducing too large damping forces increases the lateral accelerations, which is particularly undesirable in the case of buildings, where equipment and services (gas, water) could be damaged. Accordingly, accelerations should be kept below $3\,m/s^2$ [7].

Fig.3 shows the evolution of the degrading hysteresis loops with the progress of cyclic loading, for $\zeta_0 = 0.05$, $\omega_0 = 2\pi$.

4. NUMERICAL RESULTS

In this section are shown the results illustrating the modification of dynamic behaviour of buildings with two different initial values of the first vibration mode frequency and degrading hysteretic characteristics, subjected to a strong earthquake (PGA=0.5g). The time history of the ground motion acceleration, and its amplitude spectrum are shown in figs.4 and 5. It should be pointed out that the considered seismic acceleration input is represented by a narrow bandwidth signal having a dominant spectral component with frequency $f_{01} \simeq 1.2Hz$. The first case corresponds to the situation when the natural frequency of the undamaged building, $f_{01} = 1.2Hz$, is only slightly higher than the frequency of the dominant spectral component of seismic motion. In this case, the development of controlled structural degradation by allowing the occurrence of plastic hinges is expected to “pull” the system away from the vibration resonance regime.
with a beneficial effect on the building seismic response level. In the second case study, the natural frequency of the undamaged system, \( f_{01} = 1.9 \text{Hz} \), was chosen sensibly higher than the frequency of the dominant spectral component of ground motion. In this case, by structural stiffness degradation the building is “dragged” to the resonance range with an important amplification of the shear stresses that can lead to severe structural damage or even to building collapse. These two initial values of the natural vibration frequency are shown in fig. 5 as spectral lines.

and 7 display the time histories of the base-top relative displacement (drift) and of the sprung mass absolute acceleration. The evolution of hysteretic loops of the degrading structures during the seismic motion are shown in fig. 8.

The modifications of system dynamic behaviour due to structural damage were compared with dynamic behavior of the non degrading structure having the same initial structural stiffness and damping. Figs. 6 and 7 display the time histories of the base-top relative displacement (drift) and of the sprung mass absolute acceleration. The evolution of hysteretic loops of the degrading structures during the seismic motion are shown in fig. 8.
4. CONCLUSIONS

The results reported in this paper are based on simple models and possible scenarios portraying the dynamic behaviour of buildings with degrading hysteretic characteristics, during strong earthquakes. Although the model parameters and the ground motion were assigned fairly realistic values or characteristics, the simulation results couldn’t be associated with some specific real case. Nevertheless, these results advocate several important qualitative conclusions regarding the effects of structural degradation on building dynamic response to strong earthquakes:

The behavior of a building subjected to seismically forced motion of the foundation is very much dependent on whether the building natural frequencies are is shorter, approximately equal or lower as compared with the frequencies of the dominant spectral components of ground motion.

The controlled damage by allowing the occurrence of plastic hinges as the structure experiences repeated stress reversals during a strong earthquake reduces the overall building stiffness and therefore leads to a decrease of the building natural frequencies of vibration. Consequently, a building may enter or exit the resonance range of the seismically induced vibration, depending on the relative position between its initial natural vibration frequencies and the frequencies of the dominant spectral components of seismic motion. It should be mentioned that stiffness degradation can occur only for sufficiently large building deflections, which are unlikely to develop unless the building motion is excited within or very close to the resonance range. Otherwise, the building mechanical filtering properties do not allow significant amplification of the base motion or even can lead to its attenuation. Therefore, in this case the building protects itself against the seismic action.

Both the experimental and numerical simulation results presented in this paper are addressed to building seismic behaviour for resonant or quasi-resonant vibration regime. If the initial values of the building natural frequency of vibration are situated to the left side of the potential resonance range of the ground motion response spectrum, then by overall stiffness degradation the building is rapidly “pulled away” from resonance and becomes self-isolating against the seismic motion. Contrariwise, if the initial values of the building natural frequency are placed to the right side of this frequency range, then by overall stiffness degradation the building is “dragged to” the resonance range resulting in gradual development of high shear stress levels with severe consequences on building structural integrity.

The increase of the building self-damping capacity by internal energy dissipation due to development of plastic hinges is not so important as to significantly reduce the building seismic response. Moreover, the acceptance of plastic hinges is neither a safe nor an economic solution. The increase of the building damping capacity should be achieved by special devices that are capable to control and limit the structural deflections rather than by accepting the local breaking of the structural elements (beams and base columns).
The acceptance of plastic hinges occurrence in buildings, according to the seismic design standards to enhance the building strength during severe earthquakes, is beneficial only in the case in which the undamaged building natural vibration frequency is lower than the frequency of the dominant spectral component of ground motion.

By stiffness degradation the building has always the tendency to vibrate above resonance range, since a pure resonance could be possible only for extremely short time intervals. As shown in [4], for this vibration regime, the maximum values of shear forces (stresses) occur in columns at a certain height from foundation, generating in many cases column breakages at about one third of their height from the foundation level. This damaging effect is mainly due to the fact that in the above discussed vibration pattern the building base and top level absolute displacements are in opposite phase as shown by the experimental results presented in this paper.

Further work should consider more realistic models of building structural degradation as well as synthetic seismic ground motions, compatible with given design response spectra.

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