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EXPERIMENTAL INVESTIGATION OF THE SIGNIFICANCE OF THE P-DELTA EFFECT FOR RANDOMLY EXCITED STEEL COLUMNS

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ABSTRACT

The object of the experiment was to illustrate and prove that the ignorance of the P-delta effect in the calculation of the response and the failure of the randomly excited steel columns may lead to basically false result even in the case when the vertical load is relatively small. The presence of the vertical loads on the structures may cause that the direction of the successive inelastic deformations to develop not randomly, but rather tendentiously in the direction of the first considerable inelastic deformation (yielding). Because of this phenomenon the first passage time of the allowable drift limit may be much less than in the case of neglecting the effect of this geometrical nonlinearity.

KEYWORDS

experiment, steel, column, P-delta effect, random excitation, stochastic process, first passage time, ductility

INTRODUCTION

It is wellknown that the behaviour of a steel column under excitation depends on the value of the axial force acting on it. Because of the so called P-delta effect the axial force gives additional bending moment to the moments calculated by the first order theory and in this way it influences its behaviour. Although this change of the behaviour is known the P-delta effect is frequently ignored in the calculation of a real structure. The reason of this ignorance is that it is believed that if the axial force is relatively small the amount of the change is negligible.

In the laboratory of the T.U. of Budapest an experiment was designed and performed to prove that this belief is false. The aim of the experiment was to show that the presence of the vertical loads on the structures may cause that the direction of successive inelastic deformations to develop not randomly, but rather tendentiously in the direction of the first considerable inelastic deformation (yielding). Because of this phenomenon the first passage time of the allowable drift limit may be much less than in the case of neglecting the effect of this geometrical nonlinearity.

The experiment was designed to illustrate two different situations:
A./ In the first series of columns the presence of the vertical load was artificially eliminated to simulate the theoretical situation according to the analysis based on the first order theory. In this case only the inertia forces acted to the columns and the level of the displacement response was rather moderate.
B./ In the second series the same excitations were used to the columns but the vertical load was not eliminated. Hence the response was driven by the inertia forces and the vertical load. The level of the displacement response was significantly grater then in the previous case.

Sixty identical simple cantilevers were investigated. The excitation was represented by the sample functions of a stochastic process having box-type power spectral density function. One sample function was used to two columns. The first was investigated in the artificial situation the second in the real one.

TEST PROGRAM

Two series of shaking table test were performed in two different arrangement types. The schemes of the arrangements are shown in Fig.1. The names and the main characteristics of the specimens are listed in Table 1.

Table 1. Data of the specimens

Name of the specimens	Type of arrangement	Mass (equivalent mass)	Axial load / Euler load	Natural-frequency
No.84-No.113.	1	199 kg	0.0 %	1.85 1/sec
No.54-No.83.	2	199 kg	7.2 %	1.85 1/sec

In the first type arrangement made up circumstances have been created to simulate the conditions in the theoretical analysis according to the first order theory. The inertia forces were produced by a rotating balanced system of weights. No vertical load acted to the specimen. The balancing system of weights have been calibrated to produce the same inertia force as in the second type arrangement where the weights (mass) were placed directly to the specimen column and the connecting rod between the frame and the balancing weights were removed.

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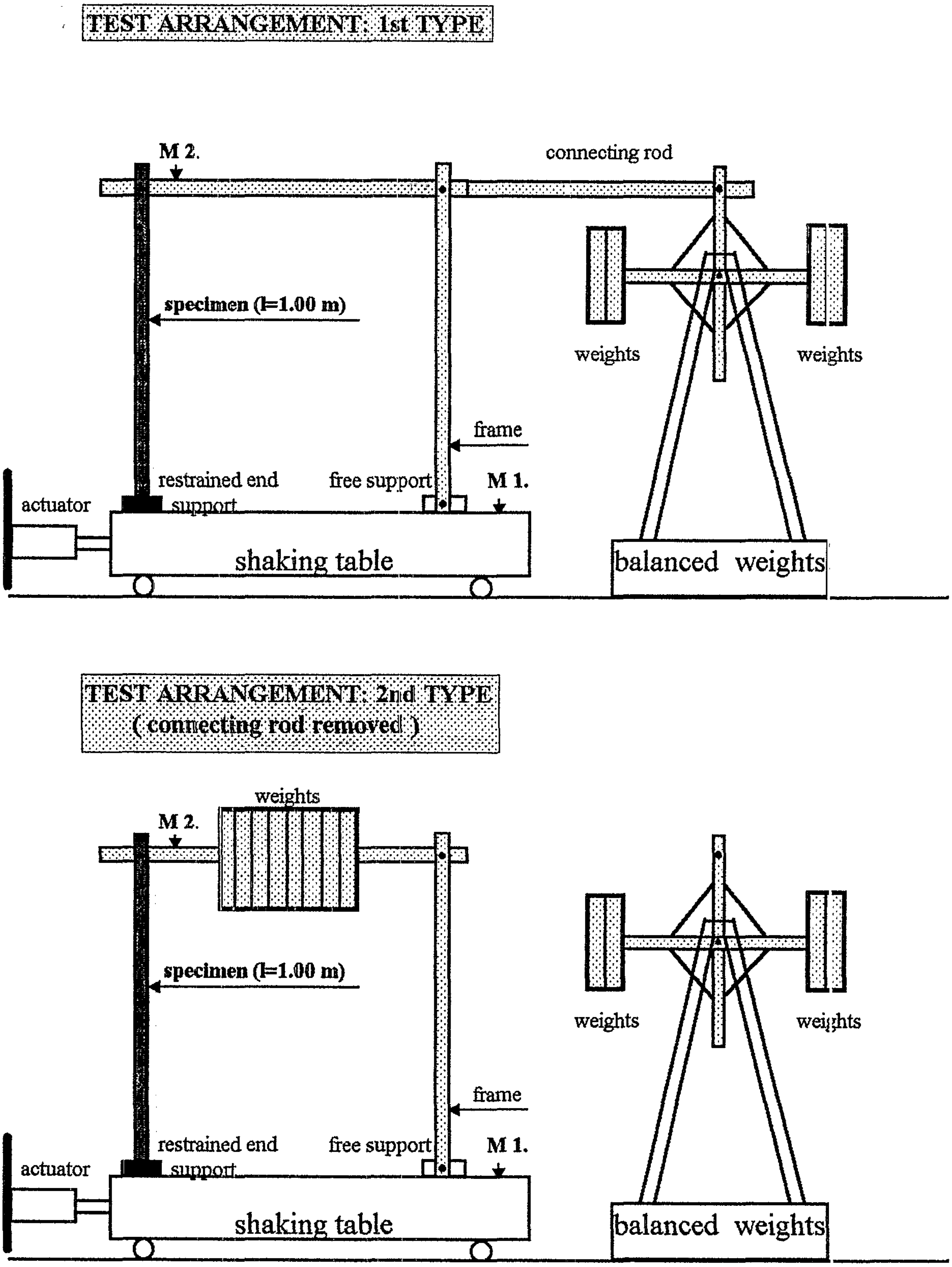

Fig.1. Test arrangements

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Data of the Test

Specimen

material : steel,
geometry: length = 1.00 m, cross section: 60x30x2 mm box,
strength : 1055-1175 N (maximal horizontal force at the top of the column),
stiffness: 25.0-25.5 N/mm (horizontal force/deflection)

Excitation

Different sample functions of a stochastic process describing the acceleration a_g of the shaking table.
Power spectral density function: box type

$$\omega_{min} = 5.0 \ \ 1/\text{sec},$$
$$\omega_{max} = 35.0 \ \ 1/\text{sec},$$
$$S_{aa}(\omega) = 0.02 \ \text{m}^2/\text{sec}^3 \quad \text{(in the one sided function)}$$

Recorded measurements

Place M1: -horizontal acceleration of the shaking table (a_g)
place M2: -horizontal acceleration of the column top (a),
-relative horizontal displacement between the column top and the table (x).

RESULTS

From the recorded data the following types of diagrams could be plotted:
- relative displacement - time (x(t)),
- hysteresis loops (a(x)),
- instantaneous state of yielding - time (Δ(t)).

(For the proper interpretation of the diagrams see Fig 2. and Fig.3. where the notations are explained.)

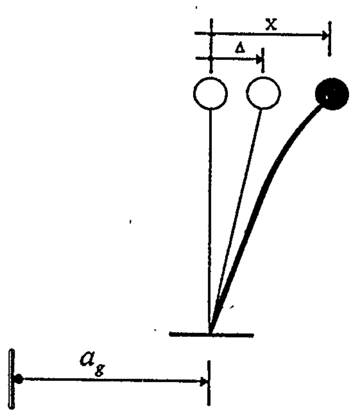

Fig.2. Simplified scheme of the SDOF system

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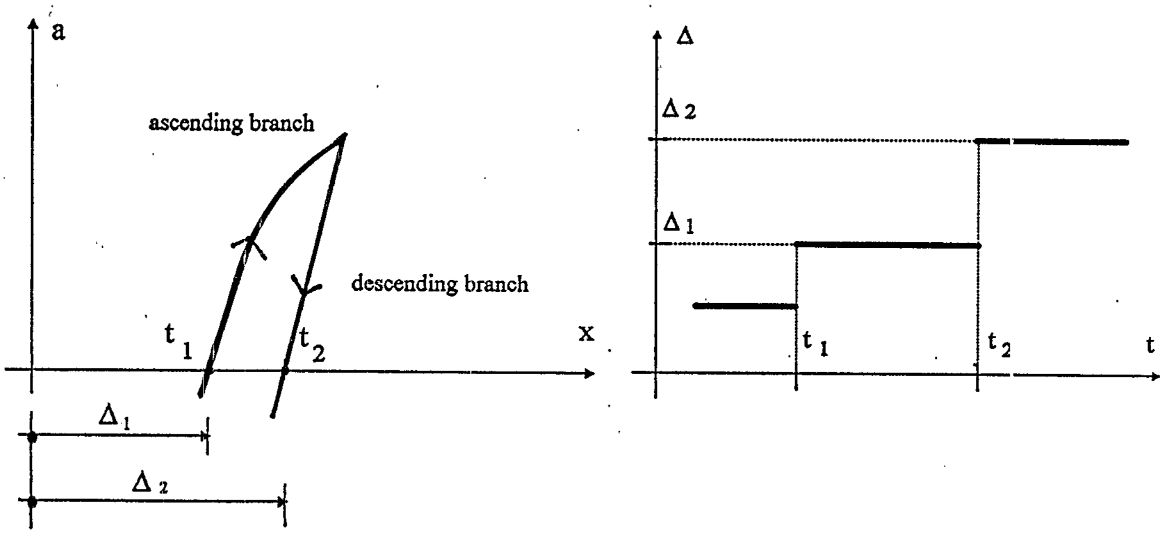

Fig.3. The interpretation of the instantaneous yielding Δ

As the illustration of the result Fig.4.,- Fig.6. show some examples of the aforementioned diagrams.
Fig.4. show two cases of excitation. In both, one can see the basic difference of the behaviour of the columns depending on the situation whether the gravity load is eliminated or not. If the gravity load acts directly to the column the successive yieldings become rather one sided and within a short period of time the column collapses. On the contrary if the vertical load is eliminated and the response is only driven by the inertia force the direction of the yielding is alternating and the column survives the excitation without too large deformations.
Fig.5. and Fig.6. illustrate the same phenomenon through the hysteresis loops. In Fig.5. when no gravity load is present, the loops are rather closed without considerable shift. In Fig.6. when the gravity load acts to the column the loops are getting to open and to be shifted from the original position.

In Fig.7. the function describing the change of the average amount of the instantaneous yielding Δ is plotted. More precisely D(Δ), the standard deviation of Δ, is calculated during the excitation period using the 30-30 recorded data series in the two different arrangement types. This figure is probably the most convincing proof for the basically different behaviour of the columns in the different circumstances. The steep increase of the function line corresponding to the real situation (when the gravity load is present) indicates that the first passage time of the allowable drift limit is much less when the gravity load is applied compared with the theoretical value calculated from the first order theory.

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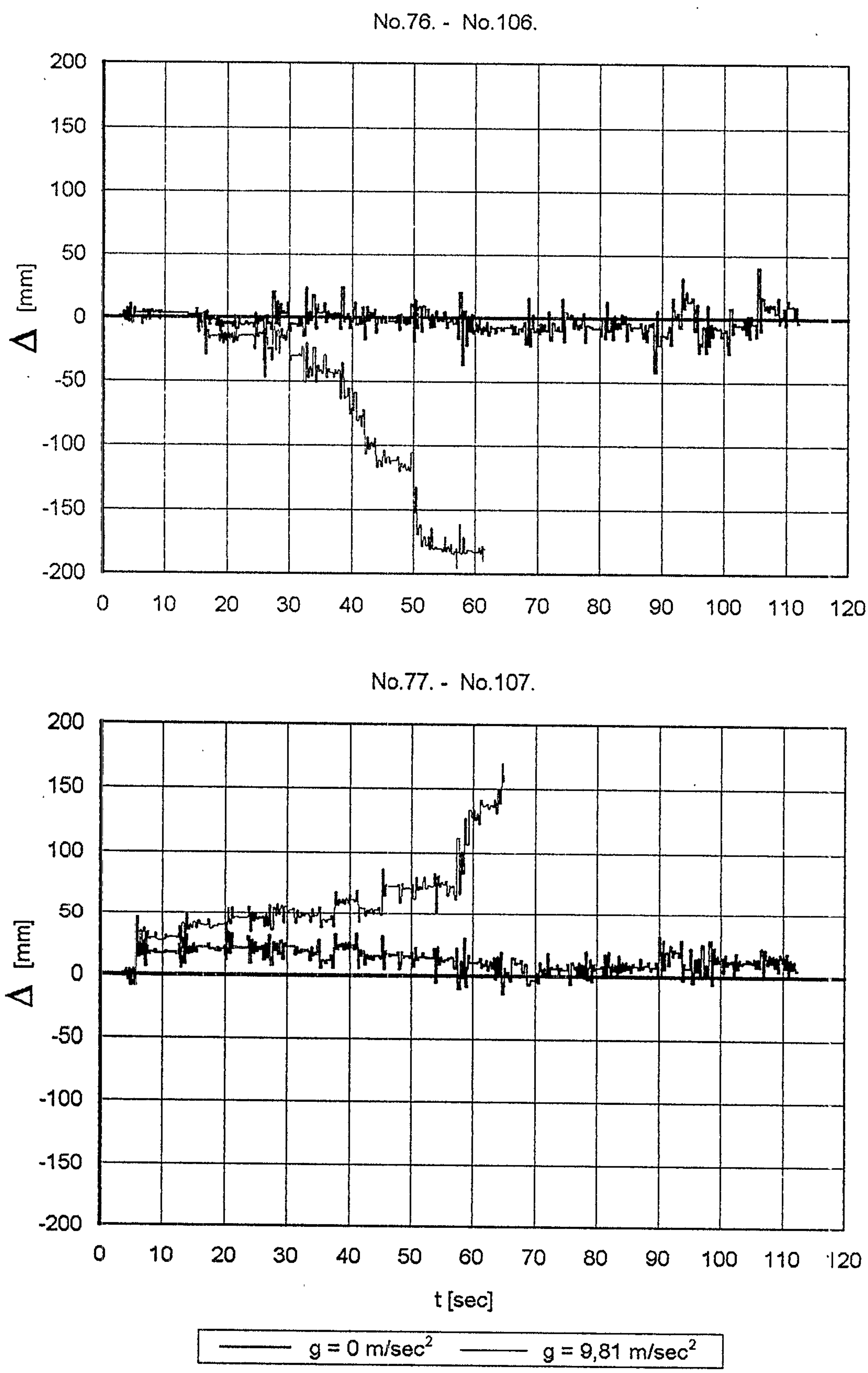

Fig.4. The instantaneous yielding in two different case of excitation

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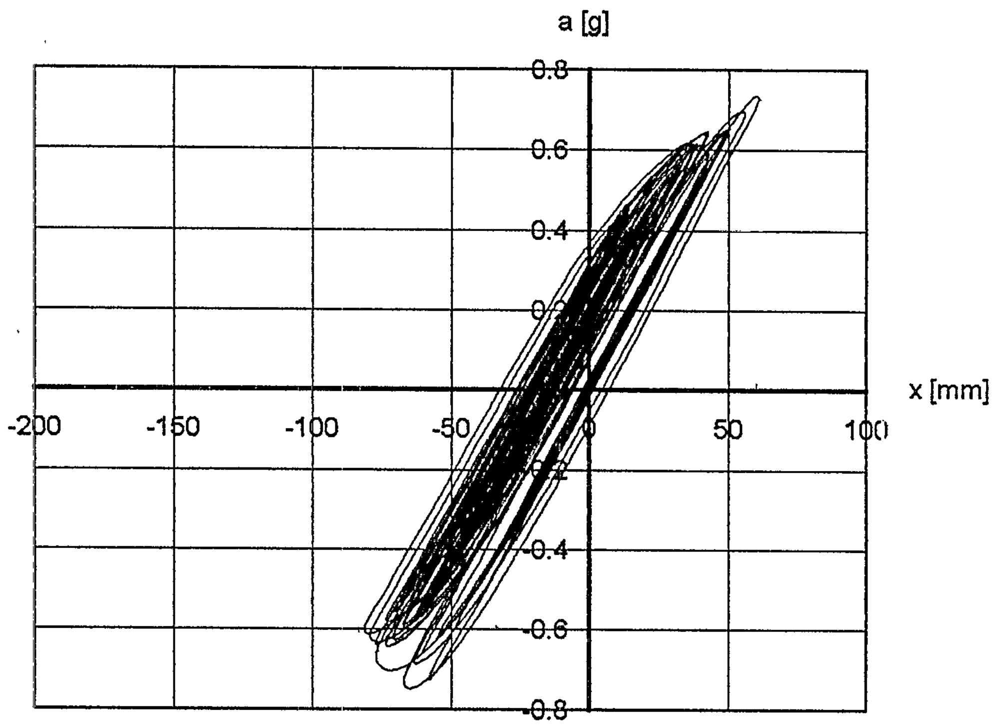

Fig.5. Hysteresis loops when the gravity force is eliminated

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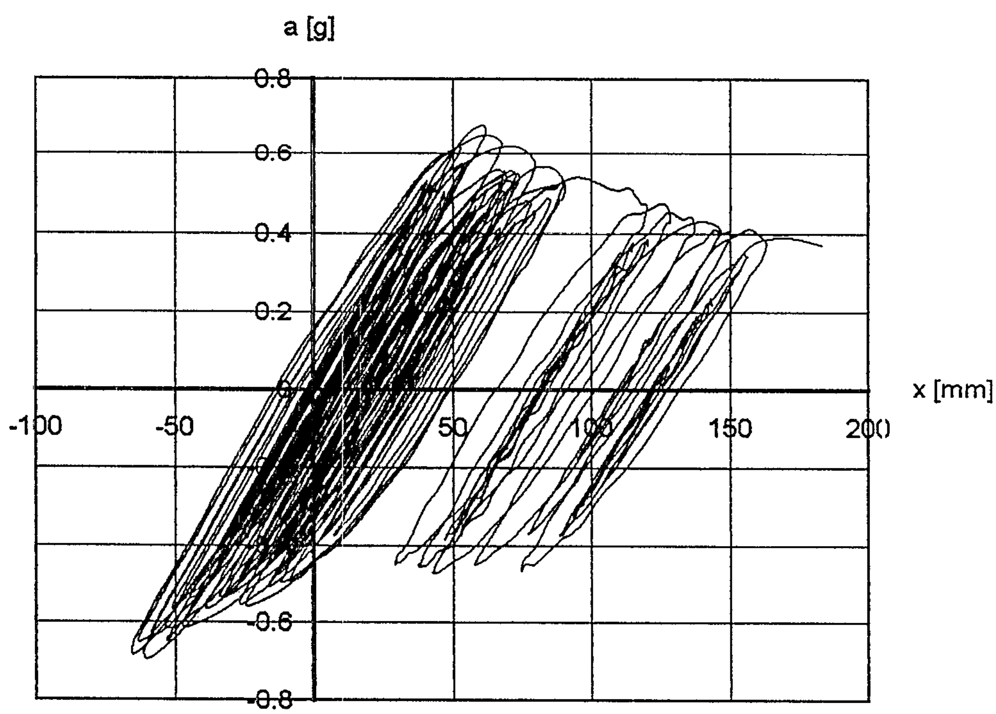

Fig.6. Hysteresis loops when the gravity load is applied

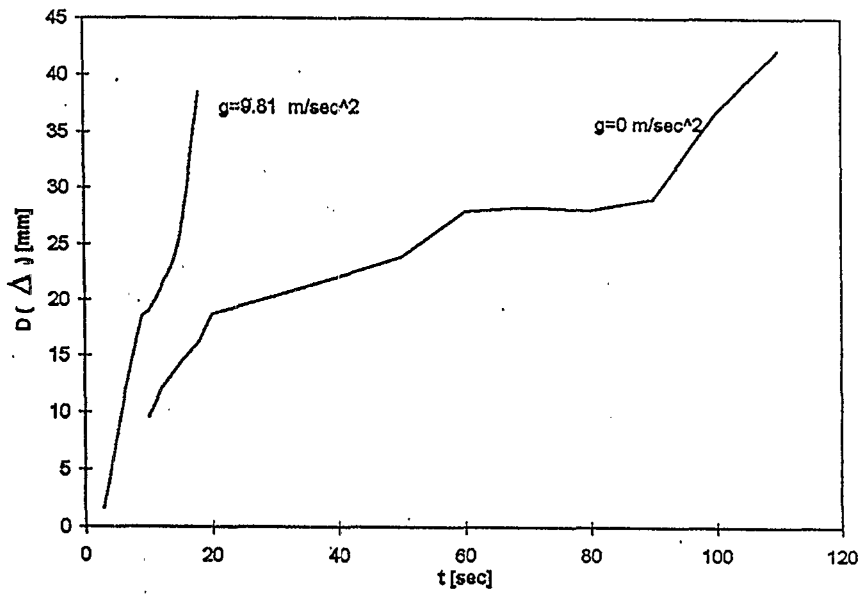

Fig.7. The change of the standard deviation of the instantaneous yielding

CONCLUSION

All of the result having got from the experience show the dramatic change in the behaviour of the columns if the vertical load is directly applied. It is despite the fact that the value of this axial load is small ($P/P_{Euler} = 0.07$) .
The theoretical explanation of this phenomenon can be summarised as follows:
After a yielding the 'neutral position' of the oscillatory system is shifted from the original position. Oscillating the system around this new neutral position the probability of a new yielding is different in the two directions. Since the gravity load gives an additional moment to the clamped end of the column the next yielding occurs at a smaller displacement response level if the displacement is in the direction of the shift. On the contrary if the direction of the next yielding is opposite to the shift the gravity load reduces the bending moment at the clamped end and the next yielding occurs at larger displacement. This is the reason why the successive yieldings occur rather tendentiously after a considerable initial inelastic deformation.
The phenomenon shown may be very dangerous for the structures operating in similar circumstances. It means that the proper consideration of the P-delta effect in seismic design is vital. The revision of the approximate theoretical consideration of the P-delta effect is necessary. Any simplified theoretical approach should reflect the essence of the phenomenon analysed above. The simple ductility concepts should also be revised to incorporate this P-delta effect.

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