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BEHAVIOUR OF REINFORCED CONCRETE STRUCTURES SUBJECTED TO SEISMIC IMPACT

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Abstract: *During various recent earthquakes impact between adjacent buildings became the cause of total or partial structural collapse. The analysis of impact effects, due to seismic actions, on the structural behaviour of different constructions was carried out and presented in this paper. The work focuses on the analysis of impact between different concrete structures of different shape and dynamic behaviour, with various gap sizes, and aims on artificially reproducing the occurrence of impact between adjacent buildings and understanding which conditions may cause structural damage and eventually collapse. Influences of different factors on impact are analysed: buildings' height, the seismic gap size and the behaviour factor q.*

Key words: *concrete structures, seismic impact, gap, behaviour factor.*

1. Introduction

The problem of impact between adjacent buildings became the cause of total or partial structural collapse during different earthquakes like Caracas 1967, Tokaki-Oki 1968, Managua 1972, San Fernando 1973, and recently Vrancea 1977, Mexico 1985, Loma Prieta, San Francisco 1989, Northridge 1994 and Kobe 1995. Despite having been designed according to the present codes for seismic areas, several structures were damaged and collapsed due to impact.

Most of the national and international codes for seismic design do not have specific provisions regarding possible impact[3]. Usually, is only specified the minimum gap size between adjacent buildings.

This gap size is different according to various codes and depends in some cases on the structure height and in other cases on the maximum displacements of each structure.

The damage caused by impact between adjacent buildings is function of: the type of structure, their dynamic behaviour under seismic actions, the gap size between structures and the relative configuration of the adjacent structures.

This study focuses on the analysis of impact between different concrete structures of different shapes and dynamic behaviours, with various gap sizes and aims at reproducing artificially the occurrence of impact between adjacent buildings and understanding which conditions may be the cause of structural damage and eventually collapse.

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2. Modelling of Impact

The structural behaviour with impact is studied using DRAIN2D [5] structural analysis program, which allows time history non-linear analysis at seismic actions.

Impact modelling is made by modifying the dynamic equations of motion whenever the relative displacements between adjacent buildings exceed the existing gap[6].

The pounding between two structures occurs if, at a certain time

$$d_1 - d_2 > \delta \quad (1)$$

where d_1 and d_2 are the displacements of each structure at the level of impact and δ is the seismic gap.

Several structures may be analysed simultaneously. In case the displacements at two given degrees of freedom (horizontal displacements of two adjacent nodes from different structures that may be subjected to impact) exceed the available initial gap, the parameters of movement are evaluated and new initial conditions of movement are imposed for each degree of freedom. These initial conditions are specified in terms of new velocities for each degree of freedom.

If at two degrees of freedom where impact occurs, the masses are m_1, m_2 and the velocities just before the impact are v_{i1}, v_{i2}, the velocities after impact v_{f1}, v_{f2} may be evaluated as follows:

$$v_{f1} = v_{i1} - (1+e)\frac{m_2}{m_1+m_2}(v_{i1} - v_{i2}) \quad (2)$$

$$v_{f2} = v_{i2} + (1+e)\frac{m_1}{m_1+m_2}(v_{i1} - v_{i2}) \quad (3)$$

where e is a *restitution coefficient* [1] related to the type of impact varying from 0 when totally plastic impact occurs and the kinetic energy is dissipated as plastic deformation energy, and 1 for a totally elastic impact without variation of the total kinetic energy.

Previous studies [2] established that, at least for a wide range of e values, the influence of the restitution coefficient is limited and suggested a value of e = 0.65 for concrete structures, which was used in the present study.

Using formulae (2) and (3) for horizontal degrees of freedom of adjacent nodes from different structures subjected to impact at a certain *time step* is possible to calculate the horizontal load at nodes due to impact, using the formula

$$Fdt = mdv \quad (4)$$

for which results the equivalent force to be applied to the k degree of freedom

$$F_k = \frac{m_k(v_{fk} - v_{ik})}{dt} \quad (5)$$

This impact simulation was implemented in DRAIN2D analysis program.

3. Impact Cases

The present studies regard the behaviour of reinforced concrete frame structures subjected to pounding. The analysis was made on regular plane frames.

Two different problems were analysed concerning the behaviour of a typical 6 storey structure in two situations:

a) impact with another structure of the same geometry (Fig. 1), but different dynamic characteristics due to different storey mass - m, different stiffness - k of structural elements and different natural frequencies - f;

The characteristics of the first 6 storey structure were maintained constant. The second 6 storey structure was designed exactly like the first one. Than, its characteristics were varied, one at the time, in accordance to the following ratios:

$$\left(\frac{m_2}{m_1}\right) or \left(\frac{k_2}{k_1}\right) or \left(\frac{f_2}{f_1}\right) = \left(\frac{1}{4} \div \frac{4}{1}\right) \qquad (6)$$

where m_1, k_1, f_1 and m_2, k_2, f_2 represent the characteristics (mass, stiffness, frequency) of the first and second structure, respectively.

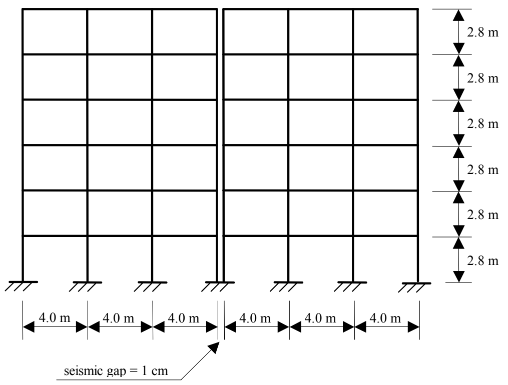

Fig. 1. *Structures with different dynamic behaviour*

b) impact with structures of different number of storeys (Fig. 2).

The first structure was the same as the first described in the previous case and the second structure was considered to have a different number of storeys (from 1 to 5).

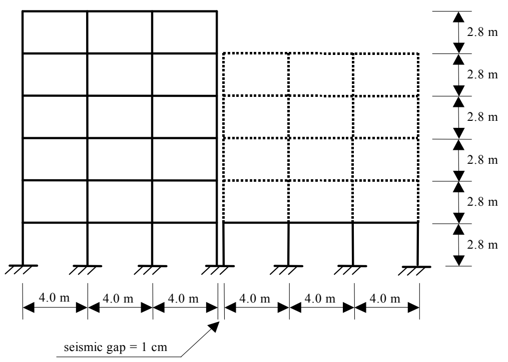

Fig. 2. *Structures with different heights*

The influence of the gap size as well as the influence of the assumed behaviour factor q were also analysed for two adjacent structures of different heights (a 6 storey structure and a 3 storey structure - the same as in previous case).

All the above-presented structures were first assumed to be alone and designed for a seismic loading according to EUROCODE 8 [4] for a stiff soil. The structures were designed assuming a q factor equal to 2.5, except when the influence of the q factor was analysed, and then subjected to artificial accelerograms. A non-linear structural analysis was performed.

For all the studied cases the following response parameters were evaluated: maximum displacements at all storey levels; maximum interstorey drifts at all storey levels; maximum required curvature ductility for all columns at each storey; maximum required curvature ductility for all beams at each storey level.

In order to quantify the effects of impact, the buildings were first analysed as structures alone and than taking into account the impact. All the above listed response parameters were evaluated and compared. The variation of storey displacements was analysed by parameter:

$$\lambda_d = \frac{d_{\max p}}{d_{\max a}} \qquad (7)$$

where $d_{max\ p}$ and $d_{max\ a}$ are the maximum displacements of the structure subjected to pounding and alone, respectively.

A similar parameter was used to assess the increase or decrease of interstorey drift:

$$\lambda_\Delta = \frac{\Delta_{\max p}}{\Delta_{\max a}} \qquad (8)$$

where $\Delta_{max\ p}$ and $\Delta_{max\ a}$ are the maximum interstorey drifts for the structure subjected to pounding and alone, respectively.

Values of λ_d or λ_Δ greater than 1 mean an increase in displacements or interstorey drift and smaller than 1 a decrease of the same parameters.

Regarding the maximum required ductility of columns and beams another parameter was defined to evaluate the influence of impact:

$$\lambda_D = \frac{D_{\max p} - D_{\max a}}{D_{\max a}} \tag{9}$$

where $D_{max\ p}$ and $D_{max\ a}$ represent the required ductility of the structure subjected to pounding or structure alone, respectively.

Positive values of λ_D mean a required ductility increase and negative values a required ductility decrease. Whenever linear behaviour was noticed, ductility was admitted to be equal to 1 and $\lambda_D = 0$.

4. Results

4.1. Impact Between Two Buildings of the Same Height

The most problematic situation of impact between adjacent buildings can be deduced from the study of the two structures presented in Figure 1, geometrically similar but physically very different.

In this case the behaviour of the first 6 storey structure (constant masses and physic characteristics) was analysed.

In each figure the ^{a} values are displayed for different storeys and different relations between the characteristics of the two structures.

Figures 3 present the variation of maximum displacements of the first 6 storey structure and give an idea of the general behaviour of a structure subjected to impact.

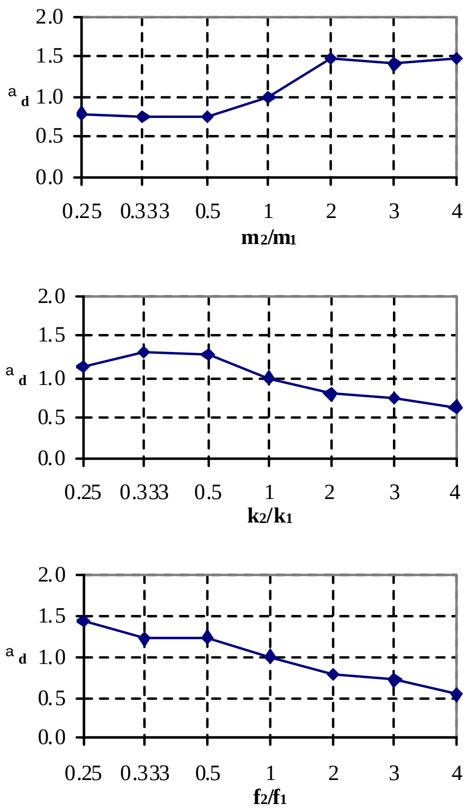

Fig. 3. $^{a}{}_{d}$ *values as function of the structural different characteristics of 2 adjacent buildings subjected to impact*

Analysing the results it can be noticed:

- λ_d increases at values greater than 1 if pounding occurs with another structure with greater mass and decreases at values smaller than 1 in case of impact with lighter structures;
- λ_d increases at values greater than 1 if pounding occurs against a more flexible structure and decreases at values smaller than 1 in case of impact with stiffer structures;
- λ_d increases at values greater than 1 if pounding occurs with another structure with smaller natural frequency and decreases at values smaller than 1 in case of impact with structures having greater natural frequency.

These results mainly show the influence of the second structure natural frequency: in case of greater mass or smaller stiffness, smaller frequencies result, with a corresponding increase of λ_d at values greater than 1.

This general tendency is also sustained by the results regarding the maximum interstorey drift (Figure 4), maximum required ductility for beams and columns.

These results are presented at all storey levels as function of the ratio between natural frequency values of adjacent structures.

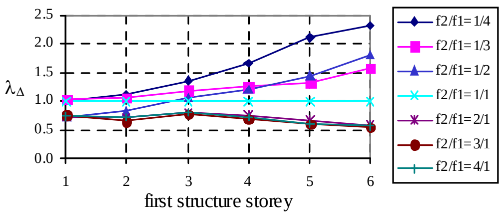

Fig. 4. ª$_a$ *values as function of natural frequencies of two adjacent buildings subjected to impact*

As Figure 4 (and similar diagrams) shows, values of λ_Δ greater than 1 are also obtained in case of impact with a structure having greater mass, smaller stiffness or smaller natural frequency. The maximum values of λ_Δ, occurring at the top storey, are greater than 2 in situations of impact with a structure having 3 - 4 times greater mass or more flexible or smaller natural frequency.

This is a general tendency for increasing λ_Δ values as one moves in height.

In the other cases, smaller masses or stiffer structure or greater natural frequencies, the analysed structure is supported by the other one, with positive effects: $\lambda_\Delta < 1$. This positive effect is almost the same regardless the level of frequency increase (Figure 4).

The λ_D values for columns may have quite great values at different floors due to local effects of pounding.

Generally, it can be noticed a higher ductility requirement for columns and beams in case of impact with structures having greater mass or smaller stiffness or smaller natural frequencies.

4.2. Impact Between Two Buildings of Different Height

The second analysed situation was the impact between adjacent buildings of different heights - a 6 storey building and another one of 1 to 5 storeys. The behaviour of the first 6 storey structure was analysed.

The second analysed situation was the impact between adjacent buildings of different heights - a 6 storey building and another one of 1 to 5 storeys. The behaviour of the first 6 storey structure was analysed.

In all cases λ values were evaluated at different storey levels for the different heights of the second structure.

Analysing the behaviour of the 6 storey structure, regarding the maximum displacements (Figure 5) it can be noticed that is a tendency for λ_d values close to 1 meaning that the taller building is sustained by the smaller building.

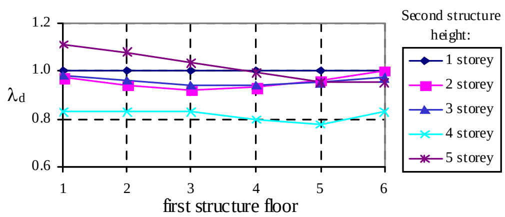

Fig. 5. ª$_d$ *values at each floor of the 6 storey structure at impact with buildings of 1 to 5 storey*

Maximum displacements only increase at the bottom storeys in the case of impact with the 5 storey building.

The impact with a 1 storey building does not occur because the gap size is too large in this case ($\lambda_d = 1$).

Contrarily to what happens in terms of global displacements, the local behaviour described by the local parameters, like maximum required ductility of columns (Figure 6), shows to be very influenced by impact.

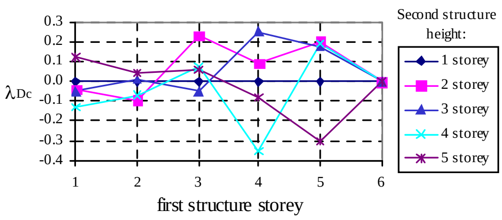

Fig. 6. λ_{Dc} *values at each storey of the 6 storey structure at impact with buildings of 1 to 5 storey*

Values of λ_{Dc} greater than 0 are noticed in Figure 6 for the first 6 storey structure at impact with all structures, regardless their heights, starting at the superior level corresponding to the maximum height of second structure. The higher values occur at the level of the top floor of the smallest structure. The displacements of the tallest structure are restrained at that level resulting an increase of interstorey drift and consequently of columns maximum required ductility at the storeys above the point of impact. The bottom storeys of the 6 storey building are restrained by the other stiffer building, thus resulting a decrease of interstorey drift ($\lambda_\Delta < 1$) and required ductility of columns ($\lambda_{Dc} < 0$). From this diagram can be also noticed the dangerous situation of impact between a first 6 storey building and a second 2 or 3 storey one ($\lambda_{Dc} > 0$).

As previously shown the impact of a 6 storey building with a 3 storey building is one of the most problematic situations. This case was studied regarding the influence of the seismic gap size values in accordance to a suggested seismic gap to avoid impact:

$$\delta = \sqrt{d_1^2 + d_2^2} \tag{10}$$

where d_1 and d_2 are the maximum displacements of each structure at the level of impact and δ is the seismic gap.

The results are presented in Figure 7 - maximum required beams ductility, where the λ values are displayed for the different storey levels and different seismic gap sizes.

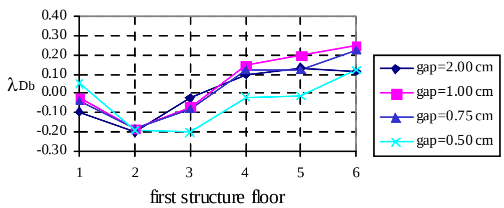

Fig. 7. $^{a}{}_{Db}$ *values at each storey of the 6 storey structure as function of seismic gap size*

The diagram of required ductility shows that an intermediate gap size of 1 to 2 cm is a very dangerous one: λ_{Db} are very amplified. If the seismic gap size decreases below 1 cm or increases over 2 cm the impact negative effects are diminished.

Higher local effects (λ_Δ, λ_{Dc}, λ_{Db}) are noticed starting with the fourth floor of the 6 storey structure, so above the impact point - third floor.

The columns behaviour at impact is very sensitive regarding the seismic gap size. This situation is illustrated in Figure 8, which presents, for the fourth storey columns, above the impact point, the values of λ_{Dc} as function of the seismic gap. It can be seen that there is indeed a tendency for reducing the impact dangerous effects for small seismic gaps and obviously to avoid them for large seismic gaps. The worst situations seem to be the ones corresponding to intermediate values.

The most dangerous seismic gap size, in this case, is between 1 and 2 cm. If the gap size is larger than approximately 2.5 cm ductility requirements are comparable to the values noticed at structures without pounding, suggesting that, in this case, this gap size could be acceptable, even being smaller than the sum of the maximum displacements.

In conclusion, for the present studies the chosen seismic gap of 1 cm seems to be indeed close to the most dangerous one.

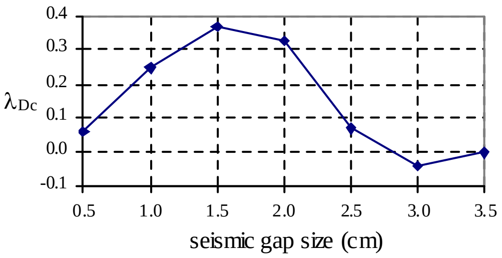

Fig. 8. ª$_{Dc}$ *values at 4 storey level as function of seismic gap size*

Studies regarding the importance of structural design at different *q* factors were performed in case of impact between two adjacent buildings of 6 and 3 storeys, the seismic gap having a value of 1 cm.

As stated in EC 8 - Part 1-3 [4], regarding the required hysteretic dissipation capacity, three ductility classes are distinguished for concrete structures: DCL (low ductility), DCM (medium ductility), DCH (high ductility).

Corresponding to these ductility classes, for regular structures as the analysed frames, result *q* factor values of 2.5, 3.75 and 5.0.

Both 6 storey and 3 storey buildings were first assumed to be alone, designed using different *q* factors and subjected to seismic accelerograms. The structural behaviour of the first 6 storey structure was studied in case of impact.

The results are presented in Figure 9 - maximum interstorey drift where the λ values are displayed for different storeys and different *q* factors.

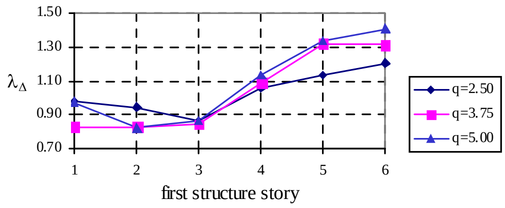

Fig. 9. ª$_a$ *values at each storey level of the 6 storey as function of q factor*

As can be seen in Figure 9 the studied parameters regarding the local behaviour show the same tendency as in previous cases: a decrease at the bottom storeys, below the point of impact (third floor) and an increase at top storeys, above the point of impact.

Generally, it can also be noticed that the λ_Δ, λ_{Dc} and λ_{Db} values increase as the *q* factor increase.

5. Conclusions

The impact between adjacent buildings can be correctly approached as presented in this study, taking into account the non-linear behaviour of materials (reinforced concrete).

In case of impact the most important parameter is the dynamic behaviour, in fact the frequency difference of the adjacent buildings.

One of the most dangerous impact situation between two structures appears when the ratio of fundamental natural frequencies is near to **2**.

In the other case, impact with another structure having higher natural frequencies, the effects are favourable for the structure with smaller frequencies, sustained by the first one. The impact occurs more frequently without damaging effects.

If impact occurs between buildings of different heights the smaller one will be normally damaged. Also the taller building is locally damaged due to the impact, especially at the level of pounding with the smaller structure. Above the point of impact, the present studies pointed an important increase of the interstorey drift and, consequently, the maximum required ductility of columns and beams. Bellow the point of impact positive effects may be noticed.

The most important parameter in preventing the negative consequences of impact is the seismic gap size. For evaluating this value a non-linear structural analysis has to be performed to find out the maximum displacements. Resulting from this study the seismic gap size has to be equal or greater than the quadratic combination of the maximum displacements of two adjacent structures and not necessary greater than the sum of maximum displacements.

Another important parameter is the behaviour factor *q*. If the structural ductility requirements are increased, as in the case of higher *q* factors, results an increased structural sensitivity (reinforcement percentages of columns and beams have lower values) and more dangerous effects of impact with adjacent buildings.

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