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Redistribution of Action-Effects on Repaired R.C. Frames

Redistribution des sollicitations dans les ossatures en béton armé restaurées

Wiederverteilung der Beanspruchung bei restaurierten Rahmentragwerken aus Stahlbeton

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SUMMARY

Some of the results of an extensive parametric study on the expected redistribution of forces in repaired/strengthened R.C. frames are presented. The principal aim of this endeavour is the estimation of the order of magnitude of the redistribution on different R.C. frames, after combined damages as well as various interventions. Some temporary conclusions concerning the re-design of damaged frames are included.

RESUME

L'article présente quelques résultats d'une étude paramétrique concernant la redistribution des effets des actions dans les ossatures des constructions en béton armé réparées ou renforcées. Le but de l'étude est de déterminer l'ordre de grandeur de la redistribution des sollicitations dans les ossatures de constructions typiques pour différentes techniques d'intervention et pour des dommages combinés. Des conclusions sont présentées pour le calcul des ossatures endommagées.

ZUSAMMENFASSUNG

Es werden einige Ergebnisse einer weitgehenden parametrischen Studie angegeben, die die Wiederverteilung der Beanspruchung bei restaurierten und verstärkten Rahmentragwerken aus Stahlbeton behandeln. Die Untersuchung wurde unternommen, um die Grössenordnung solcher Wiederverteilungen auf typische Rahmentragwerke durch kombinierte Schäden und verschiedene Eingriffe zu untersuchen, und zu einer vorläufigen Schlussfolgerung was die Neuberechnung der beschädigten Rahmen anbetrifft, zu kommen.

1. GENERAL REMARKS

The paper deals with the problems of assessment of damaged existing R.C.buildings (damages due to vertical loads as well as to earthquakes) and of re-design of such structures repaired and/or strengthened by various techniques.

In order to make decisions regarding assessment of damaged R.C. structures and remedial steps of interventions a considerable amount of data concerning pathology image and the residual structural characteristics, after damage, is needed. On the basis of such an informations a new structural analysis of the whole building is needed, in order to evaluate the redistribution of all action effects.

First of all, we must notice the different ways to take damage into account, in the different computational procedures used. For istance, structural damage may be viewed as a decreased value of the flectural stiffness (EJ), or of the shear stiffness (GA), or of the axial stiffness (EA) in particural cross-sections; also a combined damage may be viewed taking into account contemporally the reduction of the flectural as well as the shear and axial stiffnesses.This approach can be used in a linear static and dynamic analysis.
The second available approach is to consider the structural damage by means of a degrading stiffness beam model in a pre-determined loading and unloading histeretic path. Clearly, the first available approach may be viewed as a naive approach leading to very simple computations; on the other hand, the latter is much more complicated and requires to define a realistic degrading-stiffness model, what is nowdays an object of many researches in this field of investigation.
Clearly, these approaches may not be directly compared due to the different types of analysis: the former is linear, while the latter is nonlinear. So the first approach can be used to investigate an already-damaged frame subjected to a new loading condition, within the elastic range. The non linear analysis is better suitted for a " damage in progress " frame,subjected to strong static or (more often) dynamic actions.

Both the afore-presented methods have been used, in order to evaluate the redistribution of action effects after different damage degrees.

Depending of estimated or calculated bearing capacity values of the damaged structures, on emergency needs, on cost-benefit considerations, etc, several means of interventions may be adopted in order to restore or increase the capacity-ratio value of a building element or of a whole building.
Enlarged sections of repaired (strengthened columns beams or walls), infilled or braced R.C. frames etc may exhibited considerably higher stiffnesses after repair and/or strengthening. Therefore, appropriate redistribution of action-effects has to be taken into consideration, relating with vertical as well as horizontal loads.

2. REDISTRIBUTION OF ACTION-EFFECTS AFTER DAMAGE

2.1. Procedure of investigation.

The sample frames used in this parametric study are rappresentatives of common R.C. frames for low - medium - and high-rise buildings. Each sample frame has been investigated, by a linear analysis, for many possible degree of damages, starting from only one damaged sub-element up to the formation of a mechanism. The progressive damage state as well as the number and position of damaged sub-elements have been formed by another more sophistigated analysis of these sample frames based on a simple acceleration response spectrum (load-time history) of the same absolute values and on degrading-stiffness models in a predetermined loading and unloading hysteretic path.
In particular, sample plane R.C. frames (simple 3 - 5 - and 10 - storeys, 2 bays frames) have been used and static (for vertical loads) as well as a response spectrum dynamic analysis (for earthquake loads), according to the existing Ita-

lian Earthquake Resistant Code, has been developed in order to study such combined stiffness modification effects on the redistribution of action effects on damaged R.C. frames,(see Fig. 1).
Horizontal loads could have been consider by means of a static analysis, too; nevertheless it is particular significant the increasing of the fundamental period in the damaged frame. This leads to smaller values of the accelerations, to be read in the input spectrum, and hence fairly decreased inertia loads are computed. This must be taken into account when comparing the output stresses in the dynamic analysis.

2.2. Evaluation of the output results

In order to evaluate the overall behaviour between the original and the damaged frames, as well as the order of magnitude of redistribution of action effects expected on such frames, it can be attempted comparing the follovig set of data by computations of the two structures:

- Fundamental periods or frequencies, wich show the change of dynamic flexibility of the frame;
- Any norm of the generalized stess/strain or displacement vectors; particularly:

$\| S \|$ = max absolute value of the S components (stress-strain or nodal displacements)
$\| S \|_2$ = Euclidean norm, just as above.
The significant components must be restricted to the most interesting data.

In the present paper for the presentation of some of the output results the method of the Euclidean norms of the computed bending moments, shear and axial forces was computed.
So, for columns as well as for beams the Euclidean norms of the computed action-effects of the whole column line as well as of the whole bay are presented:

$$R = \sqrt{R_i^2}$$

where R_i denotes the maximum of the top/bottom value of R in an element of a column line or of a bay (R means bending moment or shear load or axial load).

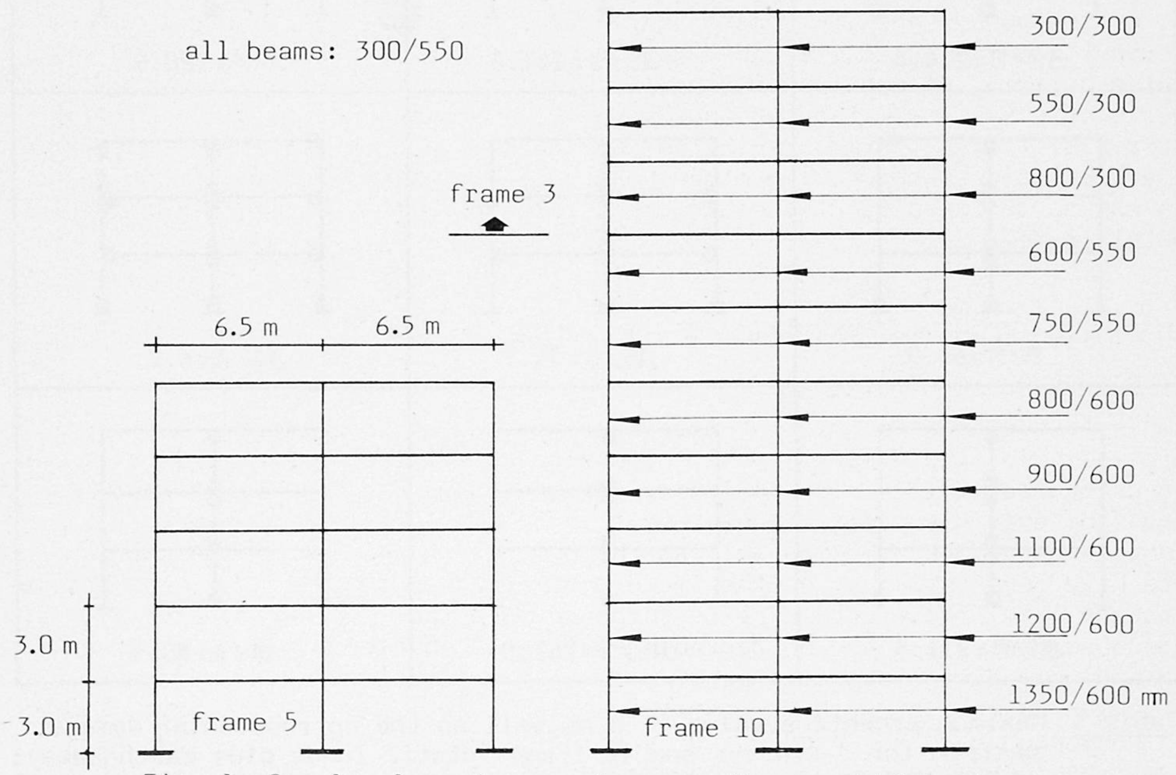


Fig. 1 Sample plane frames; low-, medium, and high rise

Percentage of stress increasing or decreasing (bend. mom., shear and axial force), is computed for " damage cases ", corresponding to various damaged sub-elements; some results are summarized on table 1.

On reference [2] a regression analysis has been developed in order to estimate the order of magnitude of such redistributions and in order to come to some temporary conclusions for civil engineering practice, as far as the "re-design" of damaged frames is concerned.

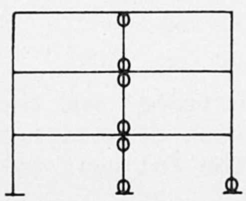
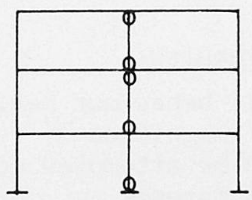
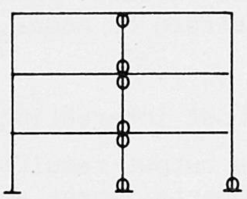
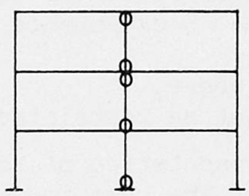
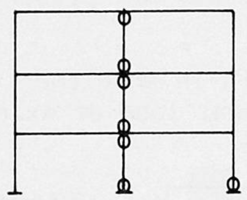
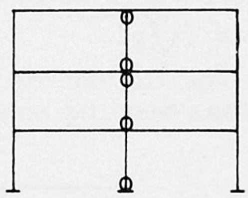
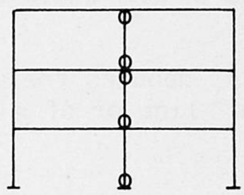
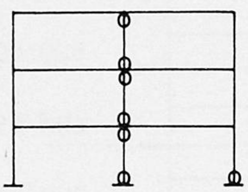
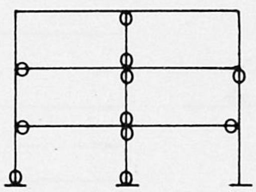
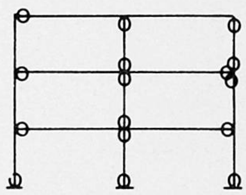
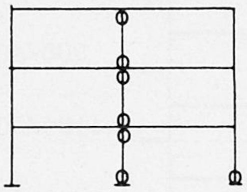
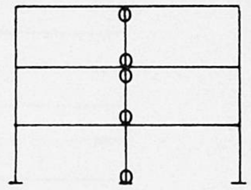
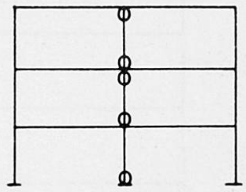
1^{st} B	 ΔM/M=145.1	 ΔS/S= 61.8	
2^{nd} B	 ΔM/M=126.0	 ΔS/S=61.8	B: Bending moment S: Shear force A: Axial force
1^{st} CL	 ΔM/M=274.4	 ΔS/S=241.5	 ΔA/A=80.5
2^{nd} CL	 M/M=61.9	 ΔS/S=34.7	 ΔA/A=6.2
3^{rd} CL	 ΔM/M=231.3	 ΔS/S=241.5	 ΔA/A=80.5

Table 1 Maximum prcentage value of R as well as the corresponding damage pattern for 3-storeys sample frame (static loads plus earthquake); ΔE/E=0.9-0.99; B:bay; CL:column line

2.3 Provisional conclusions

A detailed evaluation of percent value ($\Delta R/R$) in redistributed action-effects shows that the effects are not concentrated by the damaged subelements: rather high percent changes in stresses are also in distant beams and columns. For istance, the stresses in the upper beam may be compared, due to the lower damages.

From the analysis and the results of the above extensive investigation it becomes evident that the redistribution of all action-effects of the studied R.C. frames after combined damage is practically negligible for up to 50% damages ($\Delta E/E$=0.50). For damages more than 90% ($\Delta E/E \div 0.90$) bending and shear loads redistribution is high. Also, the redistribution of action-effects for beams is considerably lower than for columns and it has to be taken into account for heavier damages.(i.e. $\Delta E/E > 0.75$).

Another interesting general result of the above numerical analysis of various damaged R.C. frames is that natural period values are considerably higher for heavy damages (i.e. $\Delta E/E > 0.75$) than for the original state; also the decrease is more drastic and effective for high than for low-rise buildings. This has to be taken into account in the case earthquake resistance analysis is needed for the damaged frame.
Finally, the higher the frame the lower the redistribution, the more damaged sub-elements the less the redistribution.

3. REDISTRIBUTION OF ACTION-EFFECTS AFTER REPAIR AND/OR STRENGTHENING

3.1 Procedure of investigation

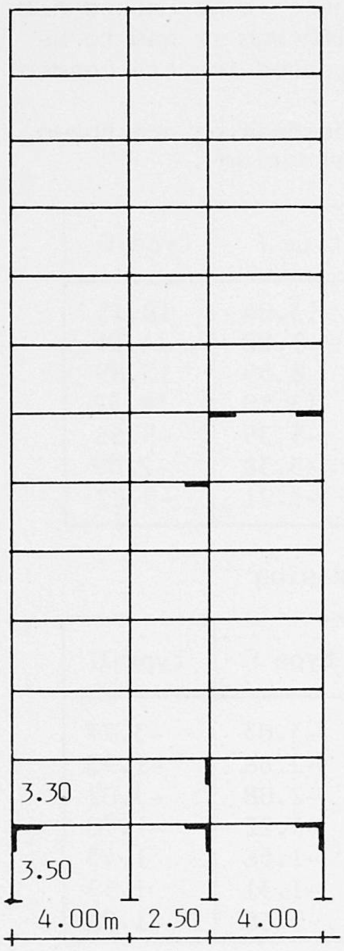


Fig. 2 Sample frame C

In what follows, different types of interventions are examined, concerning tow-dimensional R.C. frames subjected to vertical and horizontal loads, in order to study the stiffness modification effects and the order of magnitude of redistribution of action effects on these repaired and/or strengthened frames. In particular, vertical loads have been taken into account by a static analysis, while horizontal (seismic) actions have been computed by means of a dynamic response-spectrum analysis, according to Italian Earthquake Resistante Code.
Three different frames have been investigated in order to cover different types of frames, i.e. a fairly high multistory frame (12-storeys 3 bays), a middle rise frame (8-storeys 3 bays), and finally a low rise frame (3-storeys 12 bays). In Fig. 2 the general arrangement and the damaged sub-elements of high rise frame are presented.
It should be noted that such frames are not abstract and regularly shaped frames, but they are indeed practical examples of existing structures needing different interventions.
The different types of interventions taken into account are described in details in following:

Intervention type A: R.C. jackets (100 mm width), monolithic sections.
Intervention type B: The same as above, except than collaboration may not be assumed.
Intervention type C: Local replacement of damaged concrete and steel ("equal sections" method") see ref.[5].
Intervention type D: Bracing elements were introduced in a bay of the frame in all storeys.

Intervention type E: Infill R.C. walls (100 mm width) were introduced in a bay (the largest one) of the frame in all storeys.
Intervention type F: R.C. jackets (100 mm width) on all base floor columns, monolithic sections.
Intervention type G: R.C. jackets (100 mm width) on all base and first floor columns, monolithic sections.

For interventions type A, B, and C only the damaged sub-elements (see Fig. 2) were repaired/strengthened. The bracing elements were normal "X"-type light steel elements; the infilling elements have been treated as four-node isoparametric finite elements, connected to the frame nodes (only 3th bay strengthened).

For low-rise 3-storeys 12-bays R.C. sample frame, different cases of strengthening were taken into account:

St-1 (strengthening case 1): 7 infilling elements were introduced per storey in all storeys.
St-2 (strengthening case 2): 3 infilling elements were introduced just as above
St-3 (strengthening case 3): 1 infilling elements were introduced just as above

3.2 Evaluation of the output results

Three different set of data have been considered for comparison of different stiffening systems, that is: periods, stresses and displacements.
As concern stresses, the output results were summarized in the same way adopted for the damaged frames (see 2.2).

3.3 Provisional conclusions

As long as redistribution of action effects is concerned, there is no marked difference between the middle-rise and the high-rise frames, although it has to be noted that strenthening of these tow frames may lead to increased inertia loads due to decreased natural period values.
On tables 2,3 and 4 percent values of stress increasing or decreasing are shown, refered to high-rise frame (for all different types of intervention).

Element	type A	type B	type C	type D	type E	type F	type G
1st CL	-0.98	-0.77	-1.04	-23.32	-28.35	13.04	18.15
2nd CL	-1.92	-1.90	-1.62	-25.81	-30.47	8.82	14.99
3rd CL	4.71	3.35	1.93	-41.37	-52.58	8.55	13.89
4th CL	3.31	3.09	1.16	-66.31	-76.57	13.19	18.52
1st B	3.32	2.78	2.17	-11.09	-14.39	-5.35	-5.66
2nd B	11.80	9.96	8.62	-6.26	12.79	-3.38	-2.09
3rd B	4.12	3.84	2.53	-66.10	-66.85	-3.71	-5.22

Table 2 Percent values of bending moment increasing or decreasing

Element	type A	type B	type C	type D	type E	type F	type G
1st B	2.20	1.75	1.45	-6.51	-8.10	-3.03	-3.77
2nd B	6.29	5.28	5.08	-4.43	8.08	-2.86	-1.53
3rd B	2.68	2.55	1.81	-40.83	-39.56	-2.08	-3.02
1st CL	1.75	1.75	1.44	-14.84	-16.22	-1.22	-1.78
2nd CL	-1.10	-1.41	-0.83	-19.72	-22.49	-1.56	1.43
3rd CL	3.95	4.54	2.50	-41.32	-53.16	-1.31	1.53
4th CL	3.36	3.27	2.04	-76.35	-84.22	-0.68	-1.91

Table 3 Percent values of shear force increasing or decreasing

Element	type A	type B	type C	type D	type E	type F	type G
1st CL	0.44	1.02	0.25	-2.38	-2.77	-0.44	-0.38
2nd CL	0.43	0.24	0.12	-2.23	-9.22	1.20	2.05
3rd CL	1.22	0.66	0.57	3.37	-26.55	0.57	2.53
4th CL	0.39	0.23	-0.02	13.34	-29.08	-0.61	-0.43

Table 4 Percent values of axial force increasing or decreasing

It is obvious that comparison between different repairs or different structural stiffening are meaningful; it shall therefore attempt to compare type A, B, C results on one hand, and type D, E or F, G results on the other.
Concerning the first three types of repair, it could be noted that final aim is always the increasing of the sub-element stiffness, but in the cases A, B the geometric properties are changed, where in the case C the material property only is altered. Clearly, up-grading material results in linear strengthening of the section, as long as the Young modulus increases. The R.C. jackets, on the other hand, provide greatest benefits as long as cubic increasing of the section properties is achieved. Finally, it should be notice that the local strengthening generally causes an increasing of the stress values in terms of bending, shear and axial stresses at the extreme points, as could be easily shown by furtherly working out the presented results.
So, a complete survey of the upgraded structural behaviour ought to take into account other types of the results, also, just as the natural frequencies of the frame (which shows somehow a certain degree of dynamic stiffness) and its nodal displacements. Furthermore, the resulting behaviors under static and dynamic loads are signicantly different, and the final benefits ought to be found in the final load condition (static plus earthquake). This means that in the static analysis some effects may be non-positive, but this agrees with the final aim of the structural project, wich is to make the frame seismic-resistance.
The comparison between strengthening type D and E (i.e. bracing or infilling elements)is a rather complex matter to be discussed here. Shortly, a considerable reduction of the action-effects may be expected (as much as 75%) on columns as well as for beams. A significant exception is given by elements next to the stiffned bay; this may be easily explained by the fact that the node rotations and translations are strongly reduced if such nodes are connected by a shear element, so that bending moments and other stresses increase, just as by a rigid external link.
For strenthening type F and G (i.e. jackets covering the entire height of the lower floors) the redistribution of the action-effects is considerable only for bending moments on columns (approx. 10÷20% higher moments); for the beams of the frame the redistribution is negligible.
Two different probles arise for the foundations of type D and E strengthened frames; the use of bracing elements requires careful check and calculations of the load bearing capacity of the footings of columns adjacent to the braced bay, due to because of the increase of their axial load; one the other hand,the use of infilling elements requires a new heavy fondation.

Fairly significant values are shows on table 5, where the percentange of decreacing periods are recorded for the different cases and for the different periods. In the slender frames (frame C and B), the stiffening effects are "heavier" on the first period, while low rise frame (frame A) shows increasing advantages in the following periods. This accounts for a quite different behavior of different slenderness frames subjected to horizontal actions. Furthermore, the percentage plot in case A-Stl seems to be rather "flat", what may suggest that a "limit stiffening has been reached.

On the basis of these results, it should be emphasized that the period reduction

Frame	1st mode	2nd mode	3rd mode
A- St-1	12.0%	17.1%	18.5%
A- St-2	17.3%	21.1%	31.1%
A- St-3	27.3%	34.5%	48.1%
B-b	63.5%	48.5%	43.8%
B-p	55.7%	36.3%	33.8%
C-b	74.9%	55.9%	45.3%
C-p	68.7%	43.3%	31.9%

Table 5 Percentage of decreasing periods, assuming unstiffening values as 100%

Slend. ratio	1st p.lower.
3.0 ÷ 4.0	0.25 ÷ 0.35
0.3 ÷ 0.4	0.60
0.2 ÷ 0.3	0.70

Table 6 Slenderness ratio and 1st period lowering

may characterize a stiffening project. While the final aim of such an approach may be to include the period lowering (stiffened frame 1st period/unstiffened frame 1st period) in the seismic code for stiffened frames, some trial values can be nevertheless recorded here, as table 6 shows.

4. FURTHER REMARKS

As it becomes evident from the results of the above extensive investigations, the redistribution of action-effects after interventions is considerably lower than case of damages.
The change in stiffness of the repaired/strengthened elements leads to a redistribution of action effects also in distante sections; as a consequence, some non-damaged areas might need a certain strengthening or, most probably, the action effects taken into account on building components to be repair/strengthened should be increased accordingly.
Also, due to differential creep between the existing "old" element and the additional "young" ones in case of R.C. jackets of columns (enlarged sections of walls, ecc), an additional redistribution of action-effects has to be taken into consideration.

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