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NONLINEAR RESPONSE OF BUILDINGS VS.
VERTICAL REGULARITY REQUIREMENTS OF SEISMIC CODES:
A PARAMETRIC STUDY

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SUMMARY

The seismic behavior of buildings with different stiffness variations along the height is evaluated by carrying out a large number of non linear dynamic analyses. The main purpose is to check the effectiveness of some design rules of modern seismic codes relevant to design action and type of analysis. After reduction of the output data to synthetical quantities, two statistical techniques (ANOVA and regression analysis) are used to interpret and further synthesize the results. The complete methodology is illustrated and some considerations on the the results are reported.

INTRODUCTION

Irregular distributions of stiffness, strength and/or mass along the height and in the plan affects dramatically the seismic response of buildings. Most modern seismic codes contain specific rules which relate irregularities to the type of analysis for design stress calculations (static or dynamic) and to the design action intensity. Nevertheless the regularity requirements are either quantified by markedly different values or not quantified at all (Ref.1). In fact, while the qualitative aspects are well understood from the damage of past earthquakes, there is still a lack of systematic approaches for the quantitative aspects.

A research program was started two years ago to improve the quantitative knowledge of the effects of the irregularity in elevation on the seismic behavior of buildings. The main purpose was to check the directions related to this aspect of a new code recently proposed in Italy (Ref.2), which is conceptually similar to the CEB seismic code. The proposed approach is based on extensive numerical investigations on representative samples of buildings, with different changes in stiffness, strength and/or mass and on suitable statistical techniques that interpret and synthesize the results in terms of code requirements.

In Ref.3 the effects of vertical stiffness variations on the elastic response of buildings were systematically investigated. The main purpose was to quantify the differences in the strength characteristics of the buildings which are designed with either static or dynamic analysis. A sample of 72 building structures was analyzed. The main conclusion was that, as far as only design strength is considered, static analysis is conservative for buildings up to 16 stories and abrupt stiffness variations up to 80%. The present work proposes a methodology that makes use of computed nonlinear responses of R/C buildings, to assess the adequateness of code rules that relate stiffness irregularities and

number of stories to type of analysis and design action intensity. Some results are also presented and discussed.

METHOD

Two-by-six-bay symmetric R/C buildings are considered. The perfect regularity in the plan allows the mechanical characteristics of each building to be condensed into a single two-bay plane frame and therefore a big number of nonlinear analysis to be carried out at reasonable costs.

Each structure is completely designed, according to the design rules of Ref.2, by a preprocessor that assigns beam and column sizes, evaluates stresses, computes steel reinforcements, prepares the input data for a non linear analysis program. Both types of analysis and always the same behavior factor are adopted, irrespective of type and amount of irregularity. Minimum reinforcement requirements are ensured. The strength of each column is checked against the strength of the adjoining beams, according to the code rules that aim at localizing plastic hinges in beams. The non linear analyses are carried out by a dynamic non linear program (Ref.4) that allows column and beam plastic hinges to be modeled with M-N interaction strength domains and with bilinear degrading stiffness law respectively. The random character of the action is accounted for by subjecting each structure to five 15 secs. generated accelerograms, whose response spectra match the elastic spectrum associated to the design spectrum.

Four parameters are considered, namely the type of design analysis (static, dynamic), the number of stories (4, 8, 12), the number (1,4) and amount (0%, 25%, 50%, 75%, for 1 change, 0%, 20%, 35%, 50%, for 4 changes) of stiffness changes. Each structure is designed and analysed for stiff and soft ground. 84 structures have been completely designed and 420 analyses have been carried out (Ref.5).

Many state variables that give a measure of the nonlinear response of the structure from different viewpoints have been evaluated. They belong to two main groups that give a measure of the local (e.g. maximum curvature ductility, dissipated energy in beams and columns) and of the general (e.g. story displacement, interstory drift, total dissipated energy) state of the structure. In order to reduce the tremendous amount of data, some simple synthetical quantities such as the largest value (MAX.) and the coefficient of variation (C.V.) of each state variable within the same structure are evaluated for each analysis. The former gives directly a measure of the maximum response while the latter gives a measure of the uniformity of response within the structure.

Two types of statistical multivariate techniques have been used to synthesize the results: the analysis of variance (ANOVA) and the analysis of regression. The former gives a direct measure of the contribution of the single independent variables (parameters) and of their interactions to explain the total variance of each dependent (state) variable, irrespective of any hypothesized relationship between dependent and independent variables. The latter evaluates a prediction equation which is based on an assumed relationship between the dependent variable and the independent variables.

To show in some detail the proposed methodology, in this paper the discussion is restricted only to some of the results obtained for stiff ground and 1 stiffness change at half height (120 analyses).

RESULTS

The general behavior of all the structures is quite good. All the state

variables carry on acceptable values. The energy is mainly dissipated by beams (more than 90% in most cases) and the desired strong column – weak beam mechanism occurred in all cases. The behavior of columns is therefore of little interest and will not be examined.
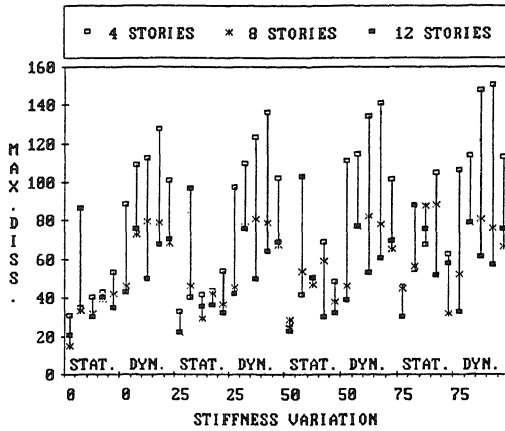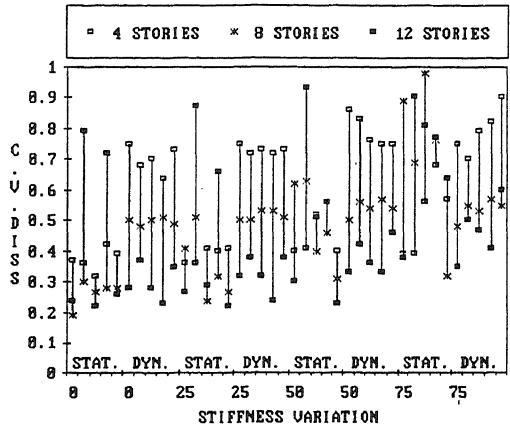

Fig. 1 – MAX. dissipated energy.
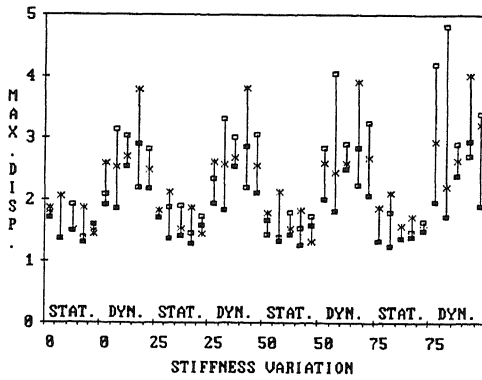

Fig. 2 – C.V. dissipated energy.

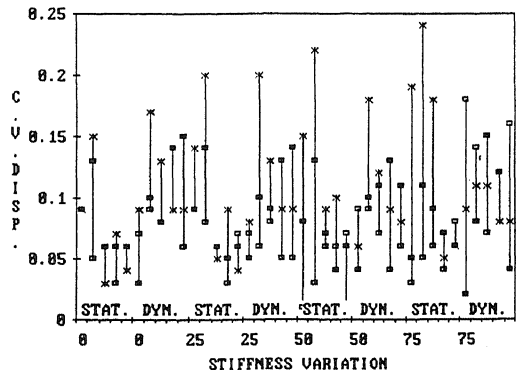Fig. 3 – MAX. story displacement.

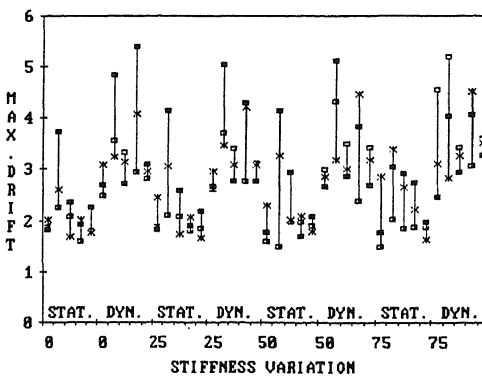Fig. 4 – C.V. story displacement.

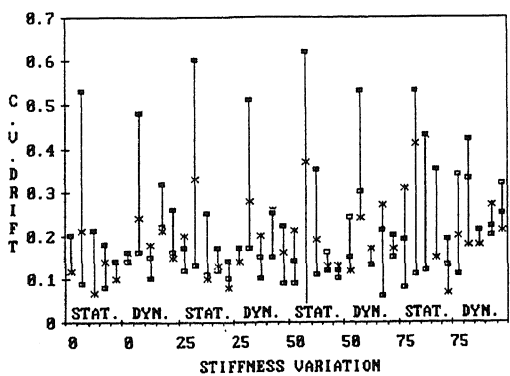
Fig. 5 – MAX. interstory drift.

Fig. 6 – C.V. interstory drift.

In figs. 1 to 6 there are shown the responses of the 24 structures to the 5 accelerograms, in terms of MAX. and C.V. of beam dissipated energy (DISS.), story displacement (DISP.), interstory drift (DRIFT). Being normalized with respect to the corresponding elastic values, DISS. is a measure of local accumulated ductility and DISP. and DRIFT represents the structure and the story displacement ductility. In each diagram the first five hi-lo lines for the same stiffness change are relevant to static while the second five to dynamic analysis designs. In the same figures also the dependence on the number of stories can be detected. These diagrams emphasize the strong influence of the type of analysis on almost all the response quantities considered. They also give a general idea of the seismic behavior and provide a visual support for the considerations that follow.

Tab. 1 - "static/dynamic" ratios of the mean value of the response.

		MAX. DISS.	MAX. DISP.	MAX. DRIFT	C.V. DISS.	C.V. DISP.	C.V. DRIFT
st./dyn.ratio		0.57	0.59	0.64	0.85	0.80	0.90
	No.STORIES						
Ratio:	4	0.42	0.54	0.55	0.57	0.62	0.57
Static	8	0.62	0.60	0.67	0.88	1.00	0.95
Dynamic	12	0.80	0.64	0.70	1.43	0.80	1.12
	STIFFN.CH.						
Ratio:	0%	0.48	0.64	0.63	0.72	0.70	0.76
Static	25%	0.50	0.62	0.66	0.76	0.88	0.90
Dynamic	50%	0.55	0.58	0.65	0.84	0.88	0.90
	75%	0.73	0.53	0.63	1.08	0.90	1.00

Tab. 2 - ANOVA: explained/total variance.

	MAX. DISS.	MAX. DISP.	MAX. DRIFT	C.V. DISS.	C.V. DISP.	C.V. DRIFT
ANALYSIS TYPE	0.332	0.557	0.441	0.039	0.029	0.007
No.STORIES	0.176	0.097	0.030	0.095	0.131	0.164
STIFFNESS VAR.	0.039	0.004	0.007	0.145	0.012	0.040
Main Effects	0.548	0.658	0.479	0.279	0.174	0.211
ANALYSIS*STORIES	0.149	0.025	0.013	0.260	0.020	0.043
ANALYSIS*STIFFNESS	0.014	0.013	0.001	0.037	0.008	0.005
STORIES*STIFFNESS	0.004	0.011	0.011	0.013	0.028	0.006
2-way Interactions	0.168	0.050	0.025	0.311	0.056	0.055
ANAL.*STOR.*STIFFN.	0.003	0.016	0.021	0.026	0.069	0.032
3-way Interactions	0.003	0.016	0.021	0.026	0.069	0.032
Total explained	0.719	0.725	0.526	0.618	0.300	0.299

A more precise idea of the influence of the type of analysis and of its interactions with the other two parameters can be drawn from tab. 1, where the ratios of the mean values of the response quantities relevant to structures designed by static and dynamic analysis are shown. The static analysis is in the mean largely conservative for all quantities (all the ratios in the first row are less than unity). It becomes progressively less conservative as the number of stories increases, because of the increasing importance of the higher modes. This trend is much more pronounced for C.V.DISS. and C.V.DRIFT, for which static analysis is no more conservative in case of 12 story structures. No trend is de-

tectable, instead, for C.V.DISP.. A similar tendency, even though less marked, is indicated when the influence of stiffness variations is considered, with the exception of MAX.DISP. and MAX.DRIFT. For C.V.DISS. only static analyses is (slightly) nonconservative for 75% variations.

The significance of the above remarks can be evaluated by referring to the (ANOVA) explained/total variance ratios shown in tab. 2. Underlined ratios correspond to effects significant at better than 5%. The explained variance ratio (last row) is generally greater for the MAX. quantities than for the C.V. quantities. The considered parameters and their interactions are particularly significant for MAX.DISS., MAX.DISP. and C.V.DISS.. Total effects (last row) and main effects (1st row) are always significant, while 2-way interactions are significant only for MAX.DISS. and C.V.DISS., 3-way interactions are never significant. The type of analysis, both alone and interacting with the number of stories, is by far the most important factor for all the MAX. quantities and for C.V.DISS. It explains more than half of the total explained variance. The stiffness variation is significant only for MAX.DISP. and C.V.DISS. but the explained variance is very small except for C.V.DISS.. The interaction between analysis and stories for C.V.DISS. is the most significant and accounts for about 1/4 of the total variance and almost half of the explained variance. The interaction between stories and stiffness is very low: these two parameters play independent roles on the seismic behavior of buildings.

Tab. 3 - Regression Analysis: coefficients and statistics.

REGR.EQUATION : $Y = ANA*(a_1 + b_1*STO + b_2*STI) + a_2*STO + a_3*STI + c$						
regress. coeffic.	MAX. DISS.	MAX. DISP.	MAX. DRIFT	C.V. DISS.	C.V. DISP.	C.V. DRIFT
a_1	91.2182	1.4501	1.2021	0.6497		
a_2	6.9342		0.0480	0.0728		0.0145
a_3	0.2064			0.0061		0.0007
b_1	-6.9875	-0.0443		-0.0604	0.0015	
b_2				-0.0023		
c	-51.3673	0.5167	0.6169	-0.4189	0.0702	0.0584
σ res.	18.2198	0.4337	0.6601	0.1295	0.0444	0.1064
σ pred.	24.7926	0.5962	0.6239	0.1450	0.0097	0.0524
μ pred.	64.8262	2.1607	2.8049	0.5097	0.0880	0.2039
expl.var. reg./ANOVA	0.9030	0.9019	0.8969	0.9001	0.1530	0.6538

In tab. 3 there are shown the regression coefficients of the equation reported in the first row of the same table (ANA is equal to 1 for static and 2 for dynamic analysis). Almost all the parameters and interaction terms significant in ANOVA enter the equation. The significant factors left out have a strongly nonlinear relationship with the dependent variable (see tab. 1). The interaction terms have almost all negative coefficients, and a negative partial correlation with the dependent variable. In the second part of tab. 3 there are shown the standard deviations of the residual and of the prediction, and the mean value of the prediction. The standard error of the residual is smaller than the standard error of the prediction only for MAX.DISS., MAX.DISP. and C.V.DISS.: these three quantities can be estimated with fairly good accuracy. In the last row there is reported the ratio between the variance explained by regression and by ANOVA. It gives an idea, when compared with unity, of the linearity of the relationship. It is equal to about 0.9 for the first five quantities, while is very low for C.V.DISP..

CONCLUSION

Completely automated design procedures and multivariate statistical analyses, such as those adopted for this study, have turned out to be indispensable and powerful tools to improve the qualitative and quantitative knowledge of the seismic behavior of buildings, when utilizing extensive parametric investigations. In particular their systematic application could lead to define well-grounded code requirements and rules on regularity of buildings.

The influence of the examined structural parameters varies when considering the seismic behavior of buildings in terms of different local and global state variables. However some general conclusion can be drawn from the results presented in this paper.

The type of analysis is the most important design factor, as it explains the most part of the explained variance, while the stiffness change turns out to be the less important. The significant interactions between "analysis" and "stories", and "analysis" and "stiffness" confirm the correctness of prescribing dynamic analyses when these two characteristics are more marked. Nevertheless the safety surplus of the static analysis, due to the overestimation (≈20%) of the participation factor of the first approximated mode, ensures better performances in terms of maximum response quantities, at least for buildings up to 12 stories and 75% stiffness change. The low interactions between stories and stiffness emphasize the independent roles that these two parameters play on the seismic behavior of buildings.

Linear laws with second order interaction terms result to be able to describe the relationship between state variables and parameters. This suggests the possibility of calibrating behavior factors by simple continuous relationship instead of assigning them discrete values.

In spite of the adoption of artificial accelerograms with uniform characteristics (same length and same elastic response spectrum), the statistical variance due to the variability of the action is often predominant. The adoption of actual earthquake accelerograms should lead to much greater total variance and considerably less statistical significance for the structural parameters. Further investigations are therefore needed, to assess the actual predictability of the seismic response of buildings on the basis solely of their design structural characteristics.

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