SEISMIC RESPONSE OF AN INDUSTRIAL STORIED BUILDING FULLY PREFABRICATED HAVING PRESTRESSED CONCRETE LINEAR FLOOR ELEMENTS OF 18 m SPAN

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SUMMARY

This paper presents a synthesis of some experimental studies and analytical investigations regarding the variation of seismic response of a new type of industrial storied building with four levels, fully prefabricated and having special prestressed floor members, subjected to seismic actions. The tests conducted up to an accentuate structure degradation, emphasized correlation phenomena between the characteristics of action and of seismic response, during various behavioural structural stages, leading to the improvement of both the computational method and the constructive requirements initially adopted.

1. INTRODUCTION

The construction of some fully prefabricated industriall buildings, complying with multiple functional requirements through flexibility of plan layout, has determined the Design Institute for Typized Construction (IPCT) - Bucharest to draw up a new type of storied industrial hall which enable to obtain increased erection speeds and to assure a better behaviour under servise loads an d especially to seismic actions.

Taking into account both the originality of the system and the fact that structure is designed for zones of high seismicity (8 degree on MM scale) it became necessary to investigate the structure experimentally.

The experimental studies were performed on a structural model at a relative large scale (a length scale of 1/2.5 within Froud Nazarov similitude criterion) tested by means of a seismic shaking table of 140 tf capacity in the Building Research Center of Iassy..

The objective of the experimental studies was to obtain quantitative data regarding the global behaviour of joints, ou joining zones as well as of component members under artificially simulated earthquake motions. The correlation of experimental data with analytical investigation were used to the foundamentation of static schemes and adequate computational methods for different working stages of structure as well as to improving the construction details in view of optimization of those types of structures.

2. EXPERIMENTAL STRUCTURE
OBJECT AND ACTIONING PROGRAM

The structure (prototype and model) was provided with reinforced concrete prefabricated columns along the whole building height (B 300 concrete mark) in which longitudinal half-beams of "L" shape are included and monolithized at the middle of span and with prestressed longitudinal members (B 500 concrete mark) of "T" shape (and variable crose section in the vicinity of supports) which rest on "L" beams as may be seen in Figs. 1, 2, 3, 4 and 5. The joints were made by lapping and welding several bars and providing a concrete casting. The first, second and third floors were provided with an overcasting. The prototype structure and the corresponding model parameters have the following characteristics: span: 18 m/7.20 m; bays: 6 x 3.0 m/6 x 1.2 m; four levels with a free height of 3.20 m/ 1.28 m; steel quality was OB 37, PC 52 and STNB for reinforced concrete members and TBP-9 for prestressed members.

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The objectives and actioning programs were selected so that to give the possibility of determining main variable characteristic parameter.

The tests into static regime, carried out with a horizontal force of 1000 kgf applied step-wise at the top level, enabled the determination of global and story effective lateral stiffness and deformed shapes, as well as the variation of beam-column angular deformation and the flexibility matrix elements δ_{44} ... δ_{41} for structure succesive working stages (initial, before cracking, at initiation of cracks, during the development of cracks and at stage of accentuate spread of cracks) as a results of earthquake actions.

The tests regarding the determination of dynamic characteristics ($T_{transv.}$ $T_{long.}$, $T_{tors.}$ and percentage of critical damping,) allowed the determination of their variation during various structural behavioural stages due to microseismic actions, small intensity shocks and strong motions as programmed earthquakes.

The tests into seismic regime, performed with the actions listed in Table 1 and used according to methodology of G.Housner and P.Jennings, forced the structure to reach its degradation stade after progressive increase of action intensities. The programmed earthquakes had beem selected so that the structural response to be maximum within a frequancy range closed to natural periors of the tested structure at a certain stage of behaviour.

The main component of the structural seismic resyonse emphasised by those experimentations supplied data for determining the seismic instantaneous global and relative lateral deformed shapes for succesive working stages, as well as the maximum envelopes of lateral displacements for various earthquake actions and base table accelerations. The acceleration distributions along the height of the building and in a horizontal plane at the first and the top level were also determined together with global first floor deformations. Another concern was the evaluation of the degree of embeding the "T" floor members into marginal beams and columns, the determination of dynamic strains at selected characteristics column and beam sections, the pursuing the manner of initiation and development of remanent cracks and emphasizing the critical zones of structure to progressive intensity actions applied by means of the shaking table.

The totality of those experimental data alowed the evaluation of certain global working stage (quasielastic, initation and development of cracks, accentuate spread of cracks) correlated with the corresponding energetic levels of actioning. The experimental results were also used as primary data for formulating hypothesis regarding the mathematical model (static schemes, embeding degree, lateral stiffness matrix elements, hysteresis structural model) by considering the physical model as a prototype structure.

3. RESULTS OF EXPERIMENTAL STUDIES AND THEORETICAL INVESTIGATIONS

The large amount of obtained experimental data makes necessary a presentation in the form of a synthesis guided on some groups of tests in different working stages up to significant degradation of structural rigidities.

3.1. Static Tests

From the analysis of experimental data it may be seen that for static test 1 (before performing the tests into seismic regime) the lateral deflected shapes are specific to frame structures (Fig.6), the displacement variation versus loads being practically linear (Fig.7) as well as in the case of rotation (Fig.8), with the exception of the last step loading relevant to the rotation at the first level. Remanent deformation at unloading were 4 percent for fourth level and 2 percent for the rest of the levels.

After initiation of the first cracks (static test 2) in the bottom level columns and in the embeding zones of the "T" prestressed members at the first level, the lateral deflected shapes changed in the sense of their closeness to the shape suited for a structure with vertical elements at which their connection with horizontal members are diminished.

The maximum drop of lateral rigidity was 22 percent (at level 4) from the initial value, while degree of beam embeding into first story columns diminished with 20 percent. Remanent deformations were less than 10 percent which prove that up to this relative strong seismic astion, the structure behaved quasielastic.

After development of cracks (static test 3) the lateral deflected shapes exhibited discontinuities with a prominent slope change at the first level, emphasizing a considerable drop in lateral stiffness. The variation of deformation versus loads presented significant slope changes, while the relative rotation between "T" members and first level columns increased 1.6 times relatively to initial stage. Remanent deformations reached values of about 10 percent which showed that for a structure with prestressed beams this value might be considered as a limit from which ireversible deformations occur.

After the stage of accentuated crack development (static test 4) lateral stiffness degradations were 81 percent for level 4, 76 percent for level 3, 79 percent for level 2 and 39 percent for level 1, as compared with initial stage. The mean lateral deformed shapes are discontinue especially at the first level, while the changes of deformation versus loads show prominent slopes with instability tendencies at last loading step. The first story relative rotations increased about 3.45 times relatively to initial stage. The remanent deformations were 10 percent larger which indicated that structure worked with ireversible cumulative remanent deformations.

3.2. Dynamic characteristics

The variation of dynamic characteristics along different behaviour stages is presented in Table 2. By extrapolating them to the prototype, the fololwing values are obtained for initial stage: $T_{transy.}$ = 0.778 s., T_{long} = 0.902 s and $T_{tors.}$ = 0.894 s while the calculated values are: $T_{trans.}$ = 0.901 s., and $T_{long,}$ = = 0.825 s. This fact shows that static schemes and stiffness matrices considered initially must be modified in the view of closening the theoretical results to the actual ones, determinated experimentally.

The formation of first cracks is marked by an increase of periods of 7-9 percent. The corresponding increase of percentage of critical damping was of 16 percent. At the ultimate stage the period increase with 14-21 percent while the percentage of critical damping increased with 80 percent.

The variation of overall lateral stiffness degradation (expressed by means of K_{44}) for the direction of seismic action (longitudinal) in term of T_{long} is presented in Fig.9. It maybe seen that for a variation of period of 21 percent, the lateral stiffness degradation of structure due to seismic actions was of 81 percent.

3.3. Seismic regime experimentations

The experimental data were selected in accordance with types of earthquakes used for: maximum accelerations of the shaking table (a_{max}), maximum accelerations recorded along structure height or in a horizontal plane ($a_{i\ max}$) structure maximum lateral displacements ($D_{i\ max}$) and maximum relative rotations between column and beam ($\phi_{i\ max}$).

The maximum instantaneous lateral deformed shapes during certain working stages for adopted earthquakes, and their corresponding instantaneous accelerations including the amplification ratios of acceleration along the height are given in Fig.10, while a synthesis of the maximum values for different tests (nonsimultaneous values) are given in Table 2. The dynamic of rotation $_i$ for succesive working stages and various actioning levels as well as the floor dynamic are presented in Fig.11 and Fig.12 respectively.

From the analysis of the experimental data it may be seen that the structure responded differentiately depending on the programmed earthquake, its intensity, the frequency distribution within earthquake record, as well as on the correlation of the deformation energy assimilation within the structure with earthquake characteristics. Their synthesis allowed to emphasize the structure working stages, presented in Table 3 for some maximum values of the seicsmic response.

Table 3

Structural behavior stage	Tests	Energetic level of shaking table $a_{o\ max}$ (m/s^2)	D_4 max (mm)	i max (minutes)
Stage I (Quasielastic)	I...V	1.20... 1.88	12.22	$_4$ = 6'57"
Stage II (Imitiation and development of cracks)	VI...XIII	1.16... 4.94	33.48	$_{max}$ = 21'06"
Stage III (Accentuated development of cracks)	XIV...XVII	1.41... 4.23	97.09	$_{max}$ = 42'06"

In the case of working stage I, the seismic average lateral deflected shapes are characteristic to the first mode of oscillation (specific to frame structure), wh while the instantaneous distribution accelerations and their amplifications along the structure height are delayed with respect tothe deflected shape for the time which corresponds to structure energy absorbtion; the first level floor worked with translationaldeformations and overall rotations assuring the role of a rigid plate, the column dynamic stress didn't exceed -260 kg/cm^2 or + 35 kg/cm^2 while the ralative rotations were smaller than the values of Ø 4.

In the stage II, which was characterized by initiation and development of cracks, the seismic lateral deformed shapes (having values of 2.85 times greater than in stage I) although remained specific to mode I, were characterized by some superpositions of higher modes, the acceleration distribution along the height being more uniform with some amplifications or diminutions which were correlated to the earthquake type and structure degradation stage. The floor of the first story presented also some overall bendings, not being any more infinitely rigid in its own plane. The column dynamic maximum stresses reached values of 509 kg/cm^2, while rotation bounded the Ø 1 maximum values.

In the stage III, of accentuate development of cracks, the seismic instantaneous lateral displacements (with values of 8 times the displacement of stage I) presented prominent discontinuities and amplifications at the top level, the acceleration distribution being quasiconstant or with some amplifications at upper stories. The relative rotations, increased of about 6.4 times with respect to the previous stage, while the floors located at the first level didn't assure the role of a rigid plate.

On the basis of Fourier spectra analysis for various stories, earthquakes used and structure behaviour stages, it may be seen that for stage I the maximum response amplifications along the height ranged around the values of structure natural frequencies in the foundamental mode. For stages II and III the spectra had also amplifications around the foundamental frequancy, ranging from 1.2 to 1.8 times with respect to base sector but the participation of higher modes increased differentially in terms of spectral composition of the programmed earthquake.

The dynamic hysteretic models for various stories ($M-\phi$ and especially $F-\delta$) for stage I and the begining of stage II are similar to those determined with alternating static forces or harmonical ones with low frequencies (models which are used at present for post-elastic dynamic analysis). As the structure underwent significant degradation of lateral stiffnesses, the shapes of hysteretic model changed in the sense that they present curvatute variations in the zone of small forces (deformations under quasiconstant force) and in an inverse sense in zones of maximum forces (force increases with limited displacements) in the form of an hardening effect.

As regard the cracking manner (the first cracks developed in prestressed floor members at support zones, then extended simultaneously to columns towards their extremities along a third of the span, to floor member at thirds and at the middle of the span, as well as in connection zone between "L" longitudinal beam and columns, Figs.13, 14, 15 and 16) the previous foundings were confirmed and it was moreover emphasized the fact that for large span floor elements, the bending moment and shear force diagrams due to seismic action moved along members and zones but also at the thirds or even at the middle of the element.

The theoretical investigations allowed to substantiate a reseacrh method for analytical model in conformity with experimental data. The model is based on the correlation which exists between the natural periods determined for certain stages and the lateral stiffness matrix trace or determinant of structure (Fig.17). This method may also be used for evaluation of structural ductility.

4. RECOMMENDATIONS

For improving the structure behaviour to strong earthquakes the following recommendations were made:

- Correction of the computational model of the structural ensemble in order to comply with experimental results in chapter 3, by considering the structural model as a prototype structure.

- Improving the structural withstanding of the supplimentary stresses due to the movement of moment and shear force diagrams corresponding to seismic action, besides the gravitational ones, in the case of large span floor member.

- Improving the reinforcement details for embeding the "L" longitudinal beam, into columns in order to avoid the inclined cracks at strong seismic actions of joints.

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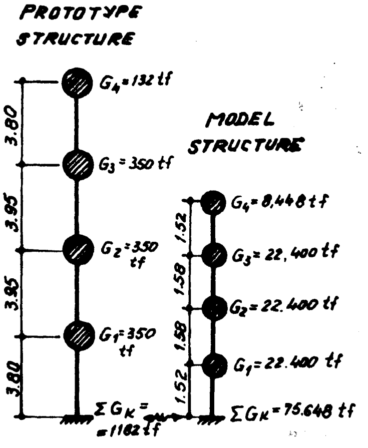


Fig. 1

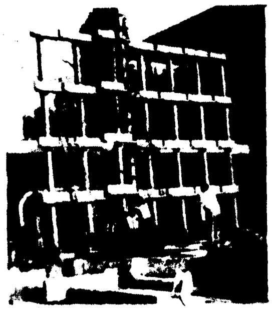


Fig. 2

Fig. 3

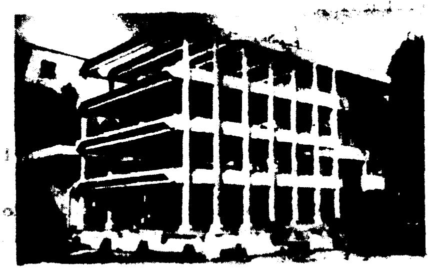


Fig. 4

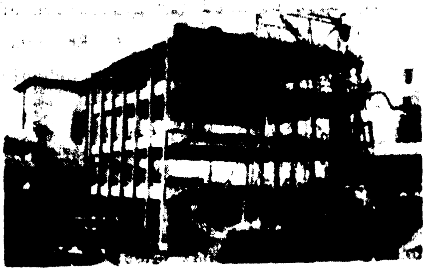


Fig. 5

Table 1.

Programmed earthquake	Actioning time (s)		Seismic intensity degree (M-M scale)
	Real	Programmed	
Artificial D2	10	10 ; 5	7 ÷ 10
Artificial C1	12	5	9
Artificial B1	50	15 ; 7	7 ÷ 9
Artificial A2	120	19 ; 13	8 ÷ 10
Artificial IAȘI	35	13	8 ÷ 9
March 4, 1977 E-V component	22	22	9
Artificial IAȘI	35	19	9 ÷ 10

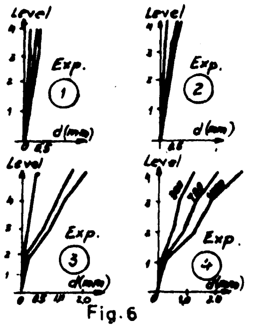
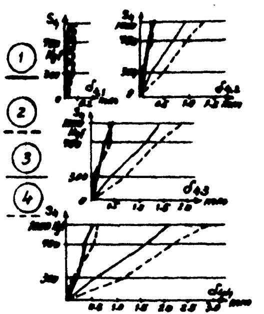


Fig. 6



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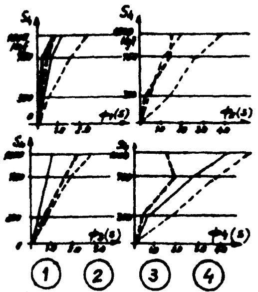
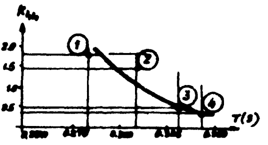


Fig. 8

Table 2.

Structure state	Action Tr.			Action Long			Action Tors.		
	Micros.	Shock		micros	Shock		micros	Shock	
	T(s)	T(s)	ν(%)	T(s)	T(s)	ν(%)	T(s)	T(s)	ν(%)
Before seismic	0.277	0.283	0.85	0.317	0.328	0.82	0.323	0.325	0.67
At the Initiation of cracking	0.297	0.307	0.96	0.340	0.347	0.97	0.340	0.347	0.81
Development of cracks	0.327	0.329	1.39	0.366	0.370	1.04	0.362	0.368	1.48
Accentuate development of cracks	0.338	0.340	1.42	0.368	0.373	1.15	0.376	0.378	1.53



Test	①	②	③	④
Period T(s)	0.283	0.307	0.329	0.340
Stiffness (mm⁻¹)	1.79	1.43	0.46	0.34

Fig. 9

TEST MAXIMUM VALUES (nonsimultaneous values)

Table 3

TEST	Accelerations a_i					Displacements D_i				Rotations ϕ_i			
Characteristics	a_{0max}	a_{1max}	a_{2max}	a_{3max}	a_{4max}	D_{1max}	D_{2max}	D_{3max}	D_{4max}	ϕ_{1max}	ϕ_{2max}	ϕ_{3max}	ϕ_{4max}
	m/s²					mm							
D_2 - 10s	1.20	1.19	1.18	1.19	2.07	1.15	4.76	5.22	4.83	2'53"	3'05"	–	–
D_2 - 5s	1.88	1.25	1.60	1.38	2.28	2.39	7.64	9.35	10.68	4'02"	4'52"	3'26"	3'51"
D_2 - 5s	1.38	1.07	1.22	1.23	2.48	2.08	5.67	7.09	8.21	3'17"	4'10"	2'27"	3'51"
D_2 - 5s	1.73	1.18	1.30	1.22	2.29	–	–	–	–	–	6'49"	3'53"	6'57"
D_3 - 5s	4.84	1.07	1.41	1.29	2.48	3.69	8.66	10.46	12.22	4'53"	6'38"	4'02"	5'29"
B_1 - 15s	4.94	2.07	2.25	1.81	2.59	8.75	17.45	21.50	24.11	15'16"	16'58"	8'37"	7'53"
B_1 - 15s	1.31	1.13	1.32	0.62	1.33	2.75	5.10	5.81	9.37	5'29"	4'57"	3'01"	7'33"
B_1 - 15s	1.16	1.51	1.51	1.56	1.94	6.13	11.47	13.25	16.24	13'09"	16'31"	6'47"	7'26"
B1 - 12s	2.26	1.88	1.60	1.64	2.85	8,00	14.27	16.50	18,75	17'43"	16'24"	7'13"	12'17"
B1 - 7s	3.02	2.02	2.82	2.05	4.19	8,76	16.05	19.52	21.59	21'06"	19'00"	8'37"	14'49"
A_2 - 19s	1,41	1.78	2,11	1.93	2.41	8.75	17.32	19.75	22,59	15'21"	16'06"	7'28"	9'20"
A_2 - 13s	1.91	1.56	2.49	2.01	3.17	8.75	17.32	19.98	18.41	12'26"	13'30"	6'39"	12'52"
A_2 - 19s	4.03	3.96	2.97	2.67	4.45	14.38	27.01	29.98	33.48	19'23"	19'49"	11'49"	15'20"
Artif. I_3 - 13s	4.23	3.16	3.53	2.92	4.06	18.13	31.85	37.42	45.20	29'33"	32'33"	16'52"	16'49"
Artif. I_3 - 13s	2.62	2.59	3.76	3.16	3.81	15.66	32.36	39.74	97.09	30'52"	29'06"	15'31"	18'48"
4.03.1977 E-V - 21s	3.32	2.35	2.96	2.87	5.08	13.39	29.56	35.79	80.77	42'06"	38'17"	17'58"	20'36"
Artif. I_5 - 19s	4.23	3.06	4.38	4.31	5.08	20.28	42.68	52.29	58.59	39'07"	45'29"	22'44"	22'24"

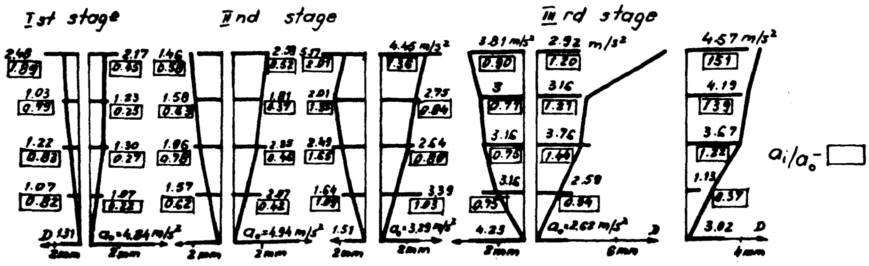


Fig . 10

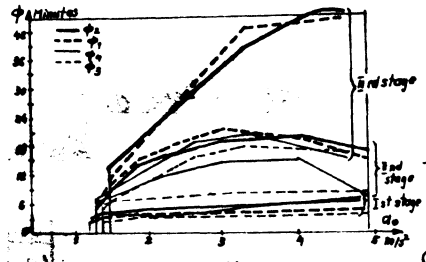


Fig. 11

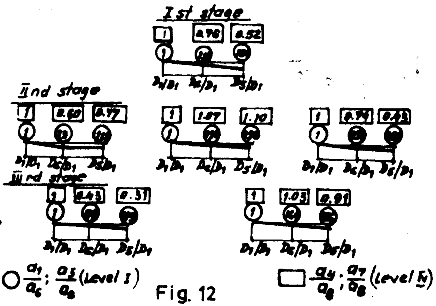


Fig. 12

Fig 13

Fig. 14

Fig. 15

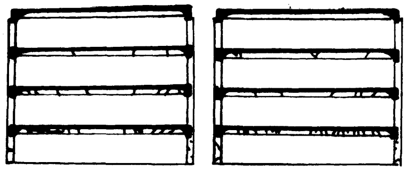


Fig. 16

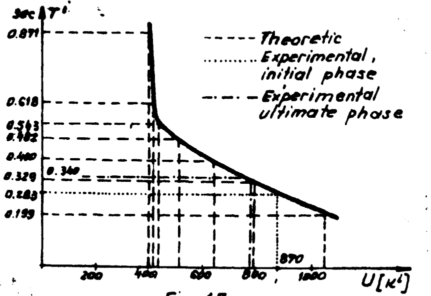


Fig. 17