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SIGNIFICANCE AND PART OF ELASTIC CONNECTIONS OF MEMBERS WITH JOINTS IN EARTHQUAKE ENGINEERING

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ABSTRACT

Theoretical base and expressions for calculation of static values and deformations in the systems with semi-rigid connections of the members in joints are given in this work. Forming of rigidity matrix of a bar with semi-rigid connections is shown depending on the fixing level of rigidity matrix and calculation of considered systems is shown on numerical examples.
Relative low level of fixing by the prefabricated connections can be favorably reflected on the distribution of the bending moments, and as such a connection is easy to be constructed, this circumstances are to be used in seismic design.
It is analyzed theoretically and experimentally the influence of elastic connections of members in joints of typical construction "MINOMA", span 27,0 m and hight 9,0 m, on the results of testing under static and dynamic load. The results obtained on the two different ways are enough close each to others. Based on obtained results, it is pointed out the significance and part of redistribution of the influences in the case of considered girders.

KEYWORDS

semi-rigid connections, rigidity matrix, redistribution of effects, static, dynamic, testing, frequency, damping.

MATRIX ANALYSIS OF SYSTEMS WITH SEMI-RIGID CONNECTED MEMBERS

In the work [1] it is analyzed, in details, theoretical approach to structural design of construction with elasticity, i.e. semi-rigid connections by means of classical slope-deflection method.
Having in mind that contemporary stress-deformation analysis of complex engineering constructions can't be imagine without matrix formulations and use of computers, in this work it will be shown just matrix formulation of analysis of systems with semi-rigid connected members [6] & [8].
Proceeding from basic rigidity matrix of elasticity fixed bar "ik" exposed to bending in the plane xoy neglecting the influence of axial forces on deformation (approximate slope-deflection method), rigidity matrix has the following shape:

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$$K=\begin{bmatrix} \frac{c_{ik}^{*}+c_{ki}^{*}}{l^2} & \frac{c_{ik}^{*}}{l} & -\frac{(c_{ik}^{*}+c_{ki}^{*})}{l^2} & \frac{c_{ki}^{*}}{l} \\ & a_{ik}^{*} & -\frac{c_{ik}^{*}}{l} & b_{ik}^{*} \\ & & \frac{c_{ik}^{*}+c_{ki}^{*}}{l^2} & -\frac{c_{ki}^{*}}{l} \\ \text{"s"} & & & a_{ki}^{*} \end{bmatrix} \qquad (1)$$

Stiffness matrix presented in [8] is shown on fig. 1.

$$[K]=\frac{EI}{l^3}\begin{bmatrix} \frac{Fl^2}{l} & 0 & 0 & \frac{Fl^2}{l} & 0 & 0 \\ & -\frac{12}{C_k}[C_1C_2+i(C_1+C_2) & \frac{6l}{C_k}C_2(2i+C_2) & 0 & -\frac{12}{C_k}[C_1C_2+i(C_1+C_2) & \frac{6l}{C_k}C_2(2i+C_2) \\ & & \frac{4l^2}{C_k}C_2(3i+C_2) & 0 & \frac{6l}{C_k}C_2(2i+C_2) & \frac{2l^2}{C_k}C_1C_2 \\ & & & \frac{Fl^2}{l} & 0 & 0 \\ & & & & \frac{12}{C_k}[C_1C_2+i(C_1+C_2) & -\frac{6l}{C_k}C_2(2i+C_2) \\ & & & & & \frac{4l^2}{C_k}C_2(3i+C_2) \end{bmatrix}$$

$$C_k=12\left(\frac{EI}{l}\right)^2+\frac{4EI}{l}(C_1C_2)+C_1C_2$$

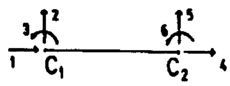


Fig. 1.

DYNAMIC DESIGN OF STRUCTURES WITH SEMI-RIGID CONNECTIONS OF MEMBERS IN JOINTS (MATRIX FORMULATION)

As difference from static analysis where external influences, as well as stress - deformation values, are independent from time, in dynamic analysis external influences are function of time. Beside basic parameters which are necessary for describing of static behavior of some system, in structural dynamics time appears as new additional parameter which significantly complicates the analysis. The number of problems, from the field of dynamic analysis of real structures, which are possible to solve analytically, are wery small. Because of that numeric methods, by use of which approximate solutions are obtained, are of particular significance in structural analysis.

Matrix formulation as method of structural analysis, at recent time particularly Finite elements method (FEM), is widely used in dynamic analysis of different engineering constructions.

Matrix formulation of motion equations

Starting from D'Alamberts principle of equilibrium of dynamic forces, the matrix formulation of motion equations of a bar can be expressed in the following manner:

$$m\ddot{q}_e+c\dot{q}_e+kq_e=Q_e \qquad (2)$$

where is:

m - mass matrix of a bar

c - damping matrix of a bar

k - rigidity matrix of a bar

Q_e - vector of generalized forces in the joints

q_e - vector of generalized displacements of a bar

$\dot{q}$ - vector of generalized velocities of a bar

$\ddot{q}$ - vector of generalized accelerations of a bar

Based on motion equations of a bar, on the usual way motion equation of a system of bars is formed.

$$M\ddot{q}+C\dot{q}+Kq=Q \tag{3}$$

where is:

M - mass matrix of systems of bars

C - damping matrix of systems of bars

K - rigidity matrix of systems of bars

Q - vector of generalized forces in the joints of system

Mass matrix and damping matrix of the system are obtained from the corresponding matrix of a bar on the same way as rigidity matrix of the system from the corresponding matrix of the bar.

The first term in the equation (3) represents inertial forces, the second one represents damping forces and the third one elastic forces of the system.

When motion equation (2) is being formed, mass matrix of a barcan be accepted as consistent mass matrix or concentrated masses matrix.

In dynamic analysis of engineering constructions, damping matrix is very importante. Mass matrix and rigidity matrix are determined without difficulties in practice design, while founding of damping matrix is very often difficult, because it is impossible to define general formula for determining of damping coefficient for constructions with different shape and made of different material. For exact defining of damping coefficient it is necessary to carry out experimental research.

Forming of damping matrix of the system C by use of damping matrix of a bar, by analogue with mass matrix M and rigidity matrix K is not possible, because it is not possible to obtain damping matrix for each finite element. So, damping matrix C is determined directly for the system, on the base of assumption that total damping of the system is equal to sum of damping that correspond to natural vibration modes of the system. So, it is applied modal superposition of damping coefficients, where system of simultaneous equation is decomposed on system of independent equations in which appear damping coefficients ξ_i (i=1, 2, ..., n).

Numerical example

For the frame shown in Fig. 2. for different fixing degrees of members in joints (cases from a to g), it is computed circle frequencies and vibration periods of free horizontal frame vibrations, as well as horizontal seismic forces according to Yugoslav regulations and maximal horizontal displacement of the frame due to design seismic loading. Having in mind that it is used approximate slope-deflection method (the influence of axial forces is neglected) as well as that inertial forces of the masses rotation are so small and can be neglected, the frame is considered as one degree of freedom system. The frame is treated as reinforced concrete one, with appropriate cross-sections of members designed for to carry permanent loading, under condition that failure happens in armature. The following dimensions of cross-sections are obtained: member 1 and 2 b/h = 50/115 cm, member 3 b/h = 50/90 cm. Elasticity modules of concrete is determined for accepted concrete strength MB30 and it is E = 3150x10^4 kN/m^2, so, for the member 3 it is EI = 1746937,5kNm^2. The weight of the structure is Q = qxl=20x25=500kN . Circle frequencies of the frame are calculated according to expression:

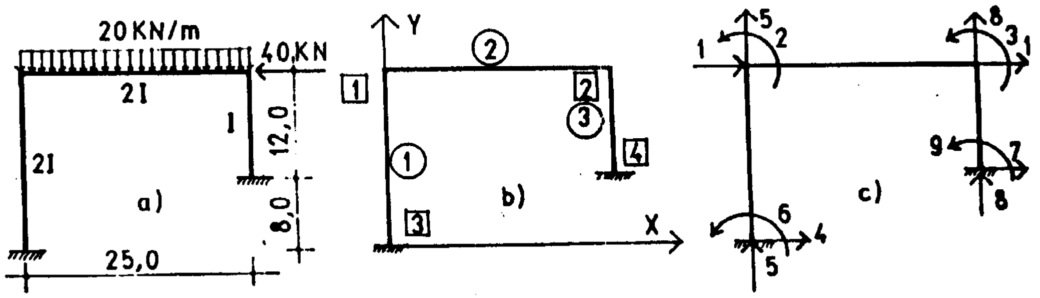


Fig. 2. a) the frame and loading, b) designations of members and joints, c) generalized displacements

$$\omega^i = \sqrt{\frac{1}{mu_1^i}} = \sqrt{\frac{gEI}{QEIu_1^i}} \tag{4}$$

where it is:

ω^i - circle frequencies of free frame vibrations (i = a to g)

u_1^i - horizontal displacement of the mass m (i = a to g)

Horizontal displacements u_1^i of the mass m are determined on the base of vector of generalized displacements qsi by use of rigidity submatrix of the frame $K_{ss}^{-1(i)}$ (i = a to g) according to the following expression:

$$q_s^{(i)} = K_{SS}^{-1(i)} S_s^{*(i)} \tag{5}$$

where is:

$$S^{*(i)} = [1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T$$

The total horizontal seismic force is calculated according to Yugoslav regulations:

$$S = KxQ = k_o k_s k_d k_p xQ \tag{6}$$

where is:

K - total seismic coefficient for horizontal direction

k_0- structure category coefficient

k_s - seismic coefficient

k_d - dynamic coefficient

k_p - ductility coefficient

In the considered case it is accepted: k_0=1 (1st category of structure), k_s=0.1 (9th degree of MCS scale), k_p=1.0 and k_d=0.7/T; 1.0 >= k_d >= 0.47 (2nd category of soil).

Maximal horizontal displacement of the frame due to design seismic forces, determined according to the Theory of elasticity, is:

$$u_{1s}^{(i)} = u_1^{(i)} S^{(i)} \qquad (\, i = a \text{ do } g \,) \tag{7}$$

and satisfies the condition $u_{1s}^{(i)}$<= H/600, where H is the hight of the structure.

The result of calculation are shown in Table 1.

Table. 1

Fixing coefficient	$EIu_1[m]$	$\omega[s^{-1}]$	$T[s]$	$k_d = 0,7/T$	$k_{d,acc.}$	$S[kN]$	$u_1^s[m]$
a) $\xi_1 = \xi_2 = \eta_3 = \eta_4 = 1$	148,998	11,22	0,559	1,251	1,0	50,00	0,0077
b) $\xi_1 = \xi_2 = 0,5; \eta_3 = \eta_4 = 1$	229,91	9,036	0,694	1,007	1,0	50,00	0,0120
c) $\xi_1 = \xi_2 = 0,5; \eta_3 = \eta_4 = 0,5$	383,26	6,998	0,897	0,780	0,780	39,00	0,0156
d) $\xi_1 = \xi_2 = 0; \eta_3 = \eta_4 = 1$	402,25	6,830	0,919	0,760	0,760	38,00	0,0159
e) $\xi_1 = \eta_3 = 1; \xi_2 = \eta_4 = 0$	505,70	6,093	1,030	0,679	0,679	33,95	0,0179
f) $\xi_1 = \xi_2 = 1; \eta_3 = \eta_4 = 0$	633,27	5,445	1,153	0,607	0,607	30,35	0,0201
g) $\xi_1 = \xi_2 = \eta_4 = 0; \eta_3 = 1$	1333,33	3,752	1,6736	0,418	0,470	23,50	0.0327

STATIC AND DYNAMIC TESTING OF "MINOMA" CONSTRUCTION

Here, it will be presented only a small part of extensive researches of typical prefabricated constructions "MINOMA" which have been tested under checking static and dynamic load.
The purpose of dynamic testing of structures is to define its real dynamic characteristics, i.e. resonant frequencies of basic modes in horizontal and vertical direction, shapes of vibration at this frequencies, as well as corresponding coefficient of visous damping. All of these parameters are the base for each mathematical modeling of construction and as usually certain analytical researches have been done previously, so it is enabled caring out of reanalyzes of stability with greater precision than it had been possible in the phase of designing.
Beside experimental determining of natural modes and frequencies, for the construction and environment in which it vibrates, it is determined experimentally damping force or force of energy absorption, as the second dynamic characteristic. The determining of this physic characteristic for different systems, considering material and construction properties, is possible only experimentally. In contemporary theory of dynamics of structures, it is usual and suitable to change damping forces at linear system that oscillate with equivalent viscous damping. Experimental determining of critical viscous damping coefficient of considered prefabricated typical constructions has fundamental significance for rational analysis of behavior and security of such constructions exposed to strong earthquake ground motions.
Testing has been done on frame structure with facade wall. Designation and disposition of measured cross-sections are shown in Fig. 3. and description of the construction is given in [7].

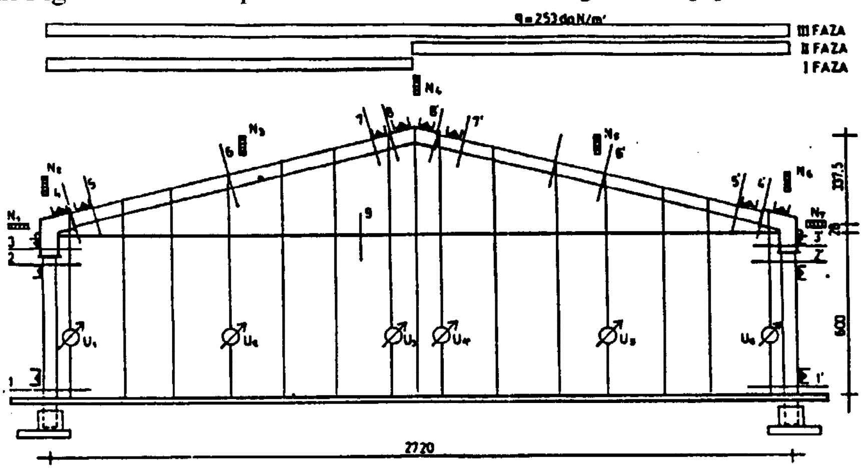
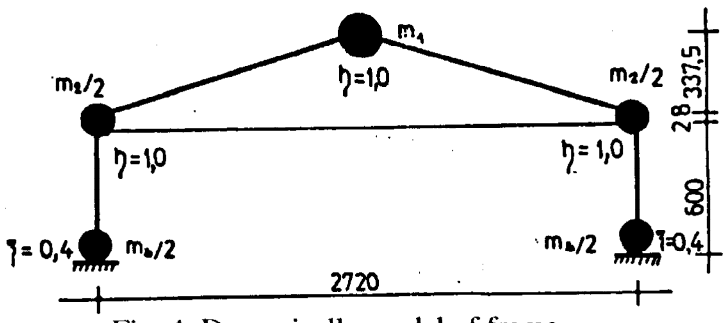


Fig. 3. Designation and distribution of measured cross-sections for static test

Static test was performed for three loading constellation in two phase:
1st phase: test up to limit of elasticity (limit of usefulness)
2nd phase: test up to failure (testing has been carried out on some elements and parts of structure)
- this phase hasn't been jet finished.

<u>Computing of circle frequencies for horizontal and vertical vibration direction</u>

On the base of experimentally determined fixing degrees of connection column to foundation ($\mu_{ki} = \eta = 40\%$) and connection column to beam ($\mu_{ik} = \xi = 100\%$) bending moments are calculated, as well as circle frequencies for horizontal and vertical vibration direction, taking in account real rigidity of connections.



$m_1 = 0{,}6mg$
$m_2 = 0{,}3mg$
$m_3 = 0{,}1mg$
$Q = mg = 10{,}352kN$
$EI = 12474kNm^2$

Fig. 4. Dynamically model of frame

Computed values of circle frequencies are:

for horizontal direction ω_h=16.26 s^{-1} =2,58 Hz

for vertical direction ω_v=22,56 s^{-1} =3,59 Hz

Results of researches

In the scope of detailed researches program, classified types of experiments have been performed. The results are given as time records of motion of material points of the structure and their mathematical processing in the form of amplitude spectrum (Furie transformation).

Experiment with forced harmonic excitation: Functional presentation of the measuring procedure, applied equipment for measuring and generating of harmonic excitation are given in Fig. 5.

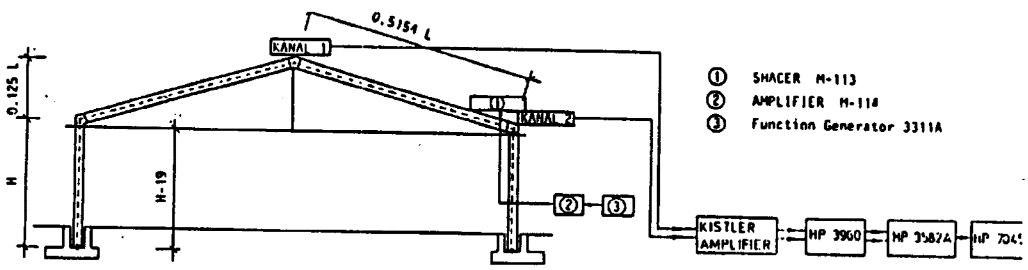
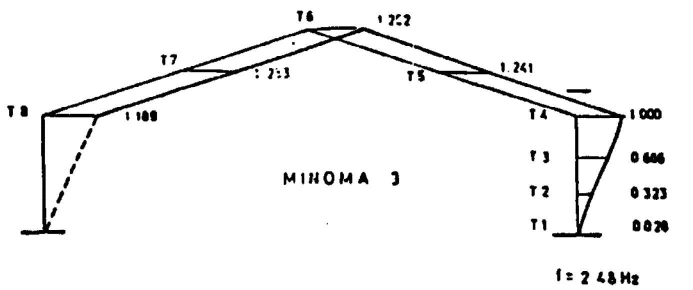


Fig. 5. Functional presentation of measuring procedure of forced harmonic vibrations and free vibrations

Obtained mode shape for horizontal direction of frame vibrations in plane is given in Fig. 6. Resonant frequent curve is given in Fig. 7.



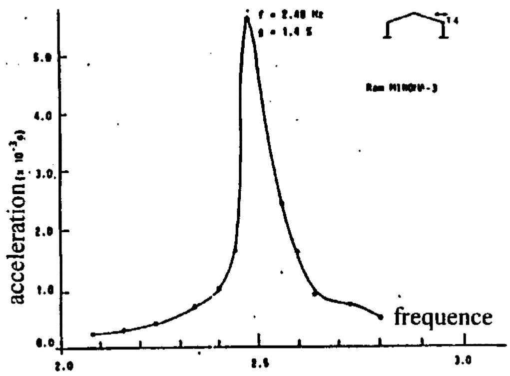


Fig. 6.

Fig. 7

Time record of dynamic structure response and amplitude spectrum for horizontal direction is given in Fig. 8.

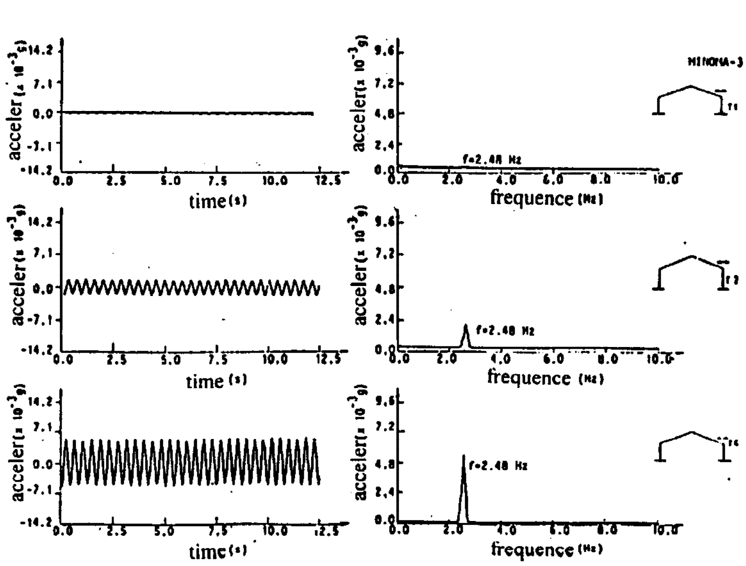


Fig. 8

Time record of harmonic decreasing functions and their amplitude spectra for horizontal vibration derection is shown in Fig. 9. and Fig. 10. This test was performed by sudden letting go of previously stretched cobble in the frame ridge.

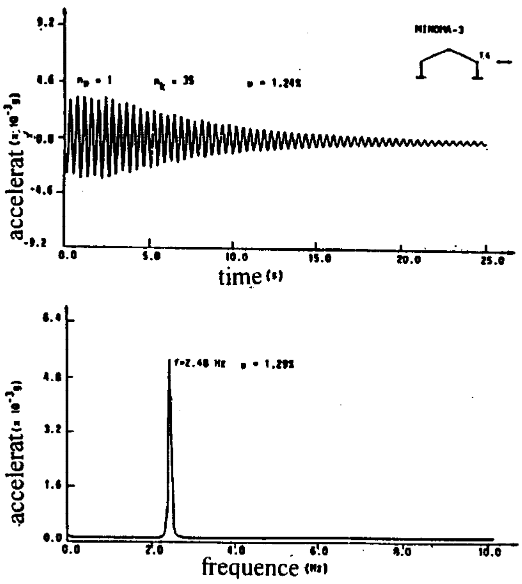


Fig. 9

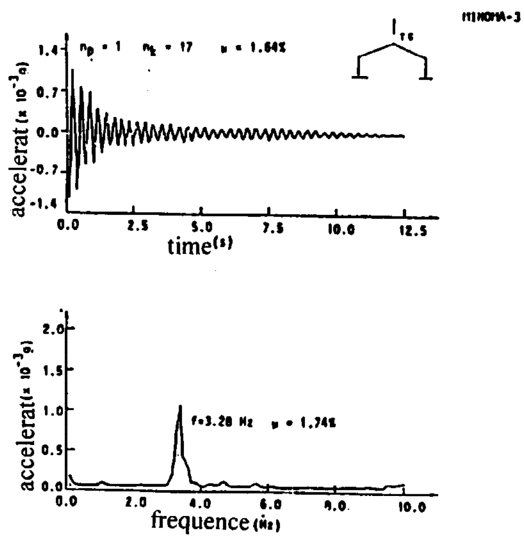


Fig. 10

<u>Experiment with ambient vibrations:</u> Functional presentation is shown in Fig. 11.

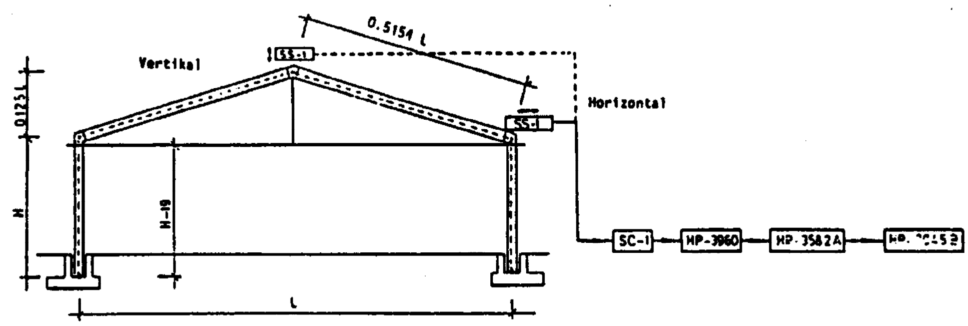


Fig. 11. Functional presentation of measuring procedure ambient vibrations

In Fig. 12 it is shown time record of ambient vibrations and their amplitude spectrum for horizontal direction and in Fig 13 For vertical direction of vibrations in the plane of frame.

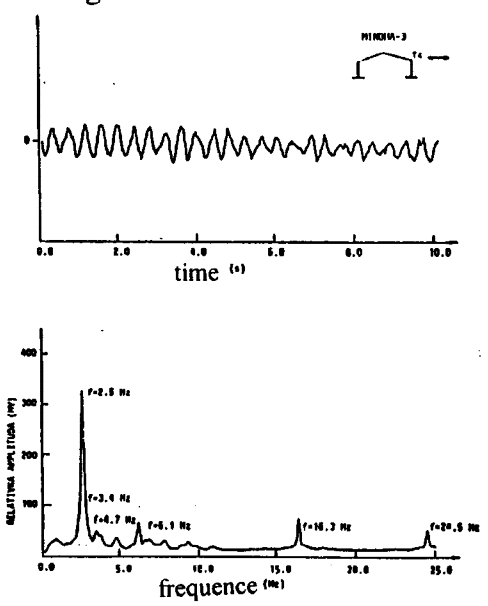


Fig. 12

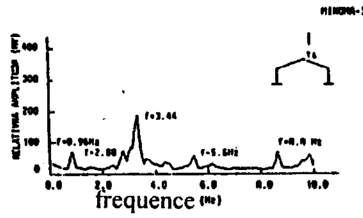


Fig. 13

CONCLUSION

It can be concluded from obtained results that fixing degree would not be neglected, both in static and in dynamic design, and particularly it would be payed attention about that, at analyze of prefabricated constructs. At static and dynamic testing prefabricated construction "MINOMA" has shown complex behavior whose details are not presented here. Experimental researches and numerical analysis of considered structure have confirmed already known data, but also have pointed out new ones, particulary in the case of prestressing by stretched cable, i. e. compensation of prestressing, as well as in the case of design of structure with semi-rigid connections of members. Calculated values of circle frequencies, based on dynamic model of the frame (Fig. 3), are very closed to measured values for both directions of vibration ($\omega_{h,r} = 2{,}58\text{Hz}$ I $\omega_{v,r} = 3{,}59\text{Hz}$).

Obtained experimental results for dynamic characteristics represent the fundament for further experimental and analytical researches that would be carried out in order typical prefabricated system "MINOMA" to get completely worth and security attest for all types of loading and influences according to available Regulation. The first that follows is exploatational testing of joints up to failure, as well as defining of design seismic characteristics (design spectra and design earthquake time histories of grammd motion). Taking in consideration that in world literature and periodicals data about damping force (expressed in term of viscous damping) are poor for considered typical prefabricated structures, obtained results represents basic values for structural analysis at strong earthquake ground motions and for estimate of global seismic security.

The authors think that it is to be pointed out to the former circumstances in the corresponding regulations and accompanied documentation (in comments or suggestions) because of missing the appropriate technical regulations for planning, designing and constructing the structures with members elasticity fixed in joints at the seismic region

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