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Dynamic Design of Systems with Semi-rigid Connections Based on Experimental Investigation of the Full Scale Structure

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ABSTRACT

Semi-rigid connections in the construction permit mutual rotation of the nodes. Since such connections are quite common in constructions, especially in the precast ones, it is of interest to determine their dynamic characteristics that is the subject of this proposed paper. During our investigation full scale experiments have been carried out and experimentally determined dynamic characteristics have been compared with those obtained by use of the computational model. The real dynamic characteristics are determined and resonant frequencies of the basic modes in the horizontal and vertical directions, the forms of vibrations at these frequencies, as well as the corresponding coefficient of viscous damping. Testing has been done on the frame structure without facade walls. For the typical precast system "Minoma 1" with span of 12m, "Minoma 2" with span of 20m, and "Minoma 3" with span of 27m, dynamic characteristics: have been determined experimentally by use of forced harmonic excitation, free oscillations and ambient vibration. Experimentally and theoretically obtained values are in a relatively good agreement that is a good starting point for mathematical modeling.

Keywords: Precast reinforced concrete structure, full scale test, dynamic characteristics, semi-rigid connection.

INTRODCTION

Dynamic calculation of structures, as it is known, consists in determination of internal displacement and stress forces due to the dynamic influences of a known magnitude and character, or testing of the system to resonance at, most often, periodically changeable loading of given predetermined frequencies. However, during the action of seismic forces, occurring during the action of the earthquake, and whose character is dynamic, the magnitude an character of the load are unknown. Several methods are used for determining the values of inertial forces amplitudes. During optimal design of actual structures a need arises to take into consideration the elasticity of nodal connections, that is, actual rigidity of connections of members in the nodes. The structures with semi-rigid joints are those systems where the connections of the members in nodes are not absolutely rigid, but permit, in the general case, a certain degree of relative displacement in the directions of all generalized displacements. It has been observed that the degree of rigidity or fixation of the connections is especially important for prefabricated and earthquake-damaged structures, influencing redistribution of static and strain values, value of critical load, length of member buckling and basic dynamic characteristics of structures. In the recent years the calculation and design of the system with semi-rigid connections in nodes are paid increasing attention.

COST 1 Project contributes to generation of necessary new understanding of the behavior of the nodes for the purpose of improving designing and safety, cost-efficiency and development and unification of approaches in design of semi-rigid connections organizing common symposiums on every alternate year.

Calculation at dynamic (particularly seismic) loads is especially important considering that the modern analysis of stress-state state of complex engineering structures cannot be conceived without the matrix formulation and application of electronic computers, in the paper was used the matrix formulation of analysis of the system with semi-rigid connections of members, which opens great possibilities for relatively quick and simple analysis of these systems with modern structural design methods. By using the matrix analysis an attempt was made to adapt the existing software packages for dynamic calculation of the structures with semi-rigid connections of members in nodes.

Such procedure facilitated implementation of the theory and contributed to the concept of semi-rigid connections finding its place in solving of practical engineering problems. Synthesized theoretical and experimental achievements in this area will be accompanied with corresponding numerical examples, and the results will be presented in tables.

DESCRIPTION OF THE TESTED STRUCTURE

This section will present dynamic testing of a standardized support structure "MINOMA" in full scale, which was constructed at the testing site of the Faculty of Civil Engineering and Architecture of Niš. The tests included two characteristic frames: that with a span of L=20 m (MINOMA-2), and L=27 m (MINOMA-3).

The beams of the frame are made of adhesive pre-stressed concrete, MB 40-50, in the form of I - profile. The dimensions of the cross section are je 35/25 cm, thickness of the web is 7cm and the thickness of the flange is 6-9 cm. The columns are made of reinforced concrete with dimensions of 35/25cm, MB30-40, reinforced by ribbed reinforcement bars, in the case of MINOMA 2, or adhesively pre-stressed of the same cross-section as the beams of MINOMA 3. The footings are designed as pre-stressed reinforced-concrete ones, with column footing fixations and anchors for connection of prefabricated or cast on-site seismic circle beams, which can simultaneously be supports of façade walls.

Between the frames in every alternate field, two-way parabolic struts made of steel cables for transversal stiffening of the frames are installed. The lengths of the elements are different and in function of the span "L", height "H" and the span between the main beams. Depending on the purpose of the structure, the roof cover may be siporeks or durisol sheets, aluminium sandwich sheets, salonit sheets etc.

The tests are conducted on a purely frame structure, without façade walls. The appearance of the tested structure was presented in the fig. 1.

DYNAMIC TESTING

Dynamic testing of the structure [6] defined their actual dynamic characteristics, that is, resonating frequencies of primary tone in horizontal and vertical directions, forms of vibrations of these frequencies as well as corresponding coefficients of viscous damping. All these parameters represent the initial basis for every mathematical modeling of the structure, and if previously certain analytical researches have been carried out, they enable performing stability analysis with far greater accuracy than in the design phase. As a rule, any natural frequency of the structure has corresponding natural form, that is, those two physical characteristics of the structure, that is, those two physical characteristics of the structure are defined by one natural (or own) oscillation tone. The lowest frequency gives a basic dynamic characteristic of the structure given and is called the fundamental natural frequency.

Determination of the fundamental natural frequency is a basic goal in experimental research of prefabricated structures MINOMA-2 and MINOMA-3.

Classification of experimental tests

Experimental tests of dynamic characteristics of standardized pre-fabricated MINOMA-2 and MINOMA-3 were conducted applying the following experiments:

(1) Experiment with ambiance oscillations is a sum of random excitations: micro-seismic activity, excitation related to human activities (such as traffic, machinery operation), wind action, etc. Analysis of time function, with the aid of Fourier's analysis, is its transformation from the domain of time into the domain of frequency, using the spectrum analyzer for field measurement or a detailed computer aided analysis. The obtained Fourier transformation (amplitude spectrum) represents a representation of time function in the frequency domain.

(2) Experiment with forced harmonic excitation offer extensive potential for testing dynamic characteristics of the standardized structure MINOMA-2 and MINOMA-3. This justifies their implementation even though it requires a longer time for conducting experiment and using of special equipment for generation of forced vibrations. The testing is conducted applying excitation vibrators, generating harmonic force, whose frequency is controlled in a specified way.

(3) Experiment with free oscillations of standardized prefabricated structure MINOMA are generated in two ways as: a) experiments with initial displacement and b) experiments when external excitation harmonic force.

APPLIED EQUIPMENT, MEASURING APPARATUSES AND EXPERIMENT PROCEDURE METHODOLOGY

In presenting the results of experimental research it is important to know the data on the structure which was tested in the experiment, as well as of the measuring instruments used. This was necessary in order to evaluate accuracy, appropriateness and applicability of obtained results in solving the problem which is the subject of the test.

The equipment for dynamic structural testing in full scale is constituted by two basic systems, which should be mutually fully compatible in terms of the range of frequency and amplitude composition. These tow systems are: a) the vibration excitation system (mechanical or electro-hydraulic exciter) and b) registration system.

Experiments with forced and free oscillations

For these tests, the used measuring equipment was : Function Generator HP-3310A, Power Amplifier Model-114, Electrodynamic Shaker Model-113, as well s istler Accelerometer Model-305A, Kistler Amplifier Model-515, Spectrum Analyser Hp-3582A, Ploter Hp-7045B (Fig.1.).

On the event of testing the considered frames with the ambient vibrations, the following equipment and apparatuses have been used (Fig.2.).

Ranger Seismometer Model SS-1, Signal Conditioner Sc-1, Tape recorder HP-3960, Spectrum Analyzer HP-3582A and Plotter HP-7045B.

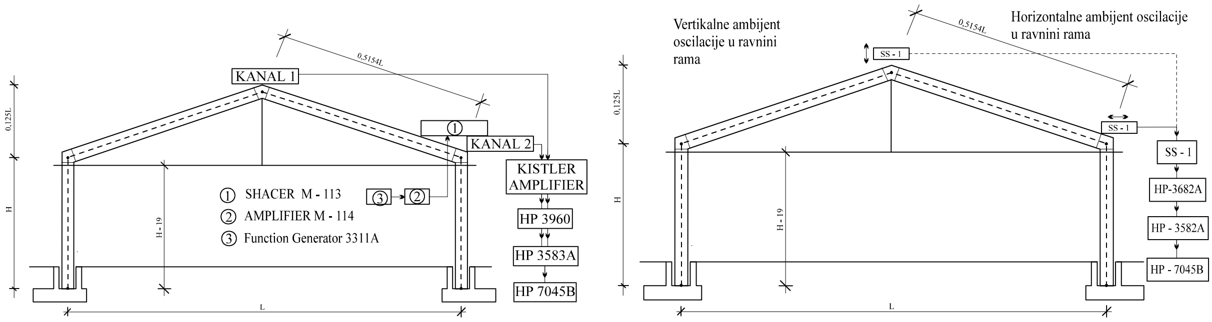

Figure1. Functional display of measuring procedure: forced harmonic oscillations and free oscillations (*left*), ambient vibrations (*right*)

RESULTS OF DYNAMIC TESTING

In accordance with the detailed testing program, all he classified experiments have been conducted. The results are presented in the form of the time recordings of displacements of material points of the structure, and their mathematical treatment in the form of an amplitude spectrum (Fourier's transformation).

For the experiment with harmonic disturbing force, a functional display of the measuring procedure course is given, and the utilized measuring equipment and harmonic excitation generating equipment have been displayed in Fig. 1. The obtained form of the tone for the horizontal direction of oscillation of the frame in plane is given in the Fig. 3, and the resonant frequency curve in the Fig. 4.

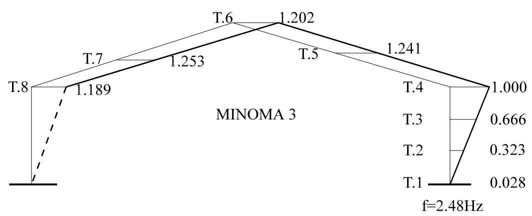

Figure 3. The form of the first mode oscillation in horizontal direction

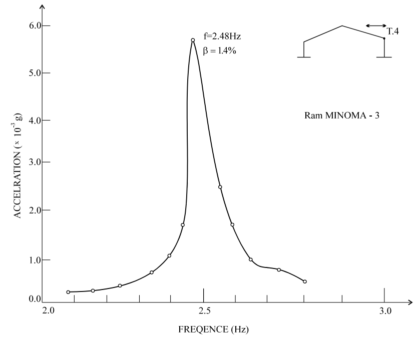

Figure 4. Resonant frequency curve

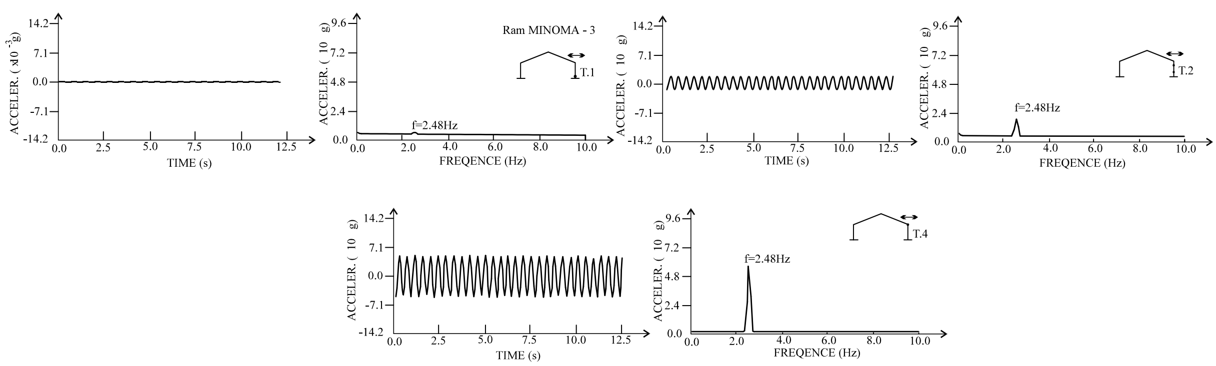

Figure 5. Amplitude spectra for horizontal direction

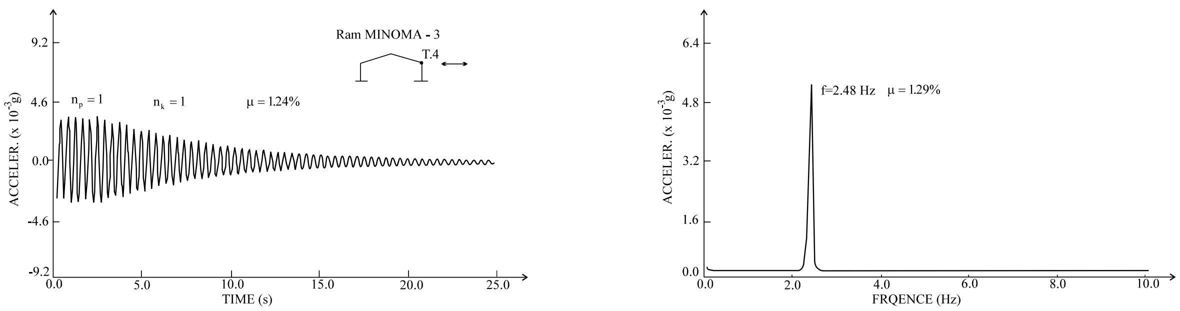

Figure 6. Amplitude spectrum for horizontal direction for harmonic decreasing function

The measured circular frequency of the first primary tone is f = 2,48 Hz and the damping is 1,4%. The time recordings of the dynamic response of the structure and their amplitude spectra for the horizontal direction are given in the Fig. 5.

In Fig.6 the time recording of harmonic decreasing functions has been displayed and their amplitude spectrum for the horizontal direction of oscillation. This test was conducted by the abrupt releasing of a previously tensioned cable in the angled ridge.

For the experiments with ambient vibrations, the functional display of the measuring procedure course and the utilized equipment are given in the Fig.2. In Fig.7 is displayed the time recording of ambient oscillations and their amplitude spectrum for the horizontal direction, and in Fig.8 the amplitude spectrum for the vertical direction of frame oscillation.

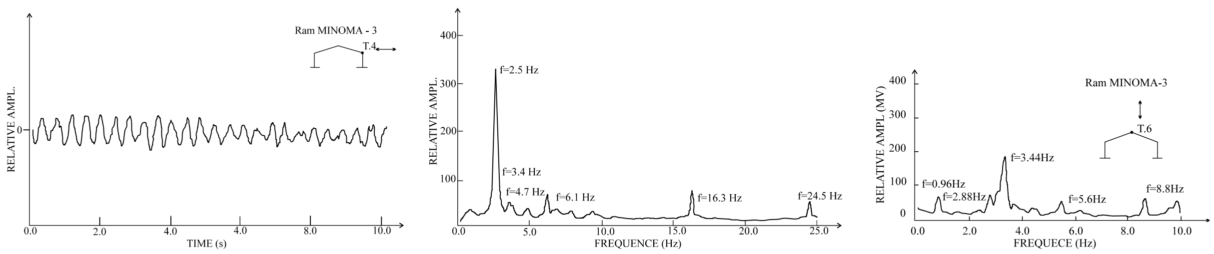

Figure 7. Time records of ambient oscillations, amplitude spectrum for horizontal direction of oscillations, amplitude spectrum for vertical direction of oscillation, respectively

Calculation of frequencies for horizontal and vertical direction of oscillation

On the basis of experimentally determined degrees of fixation of the connection of the column and the foundations ($\mu_{ki} = \eta = 40\%$) i.e. of the connection between the column and the beam ($\mu_{ik} = \xi = 100\%$) an actual dynamic model of the frame was formulated and presented in Fig.9 and the circular frequencies of free oscillations for the horizontal and vertical direction of frame oscillations have been calculated.

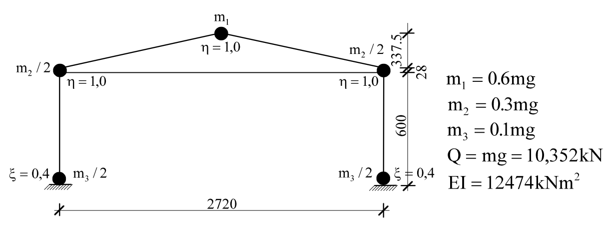

Figure 8. Dynamic model of the frame

The following values of calculation circular frequencies have been obtained: for the horizontal direction ω_h=16.26 s^{-1} =2,58 Hz, for the vertical direction ω_v=22,56 s^{-1} =3,59 Hz.

By comparing the measured values of frequencies of the first primary tone of the structure for the horizontal direction ω_h=2,48Hz and the vertical direction ω_v=3,44Hz with the calculated values, it can be concluded that the differences are very small and amount to around 4% in both directions.

DYNAMIC DESIGN OF THE STRUCTURES WITH SEMI-RIGID CONNECTIONS

The matrix form as a method of structural analysis, and especially the finite element method (FEM) in the recent period, have found wide application in dynamic structural analysis in various areas of design engineering. For the frame in Fig.10 the calculated values are given in the Tab.2.

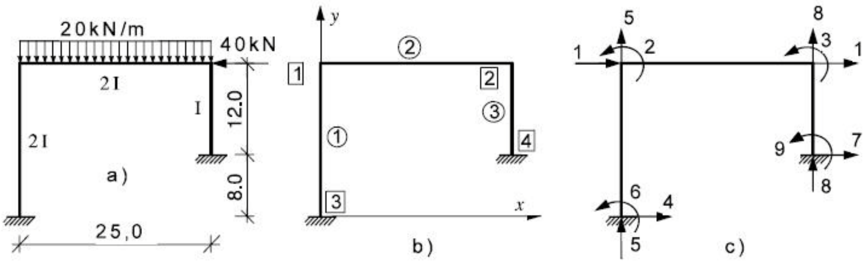

Figure 9. a) beam and load, b) designations of members and nodes, c) generalized displacements

Table 1. Various degrees of fixation

node	Degree of fixation	a	b	c	d	e	f
1	ξ	1,0	0,5	0,5	1,0	1,0	0
2	ξ	1,0	0,5	0,5	0	1,0	0
3	η	1,0	1,0	0,5	1,0	0	1,0
4	η	1,0	1,0	0,5	0	0	1,0

The values in the table 2. are calculated according to the Regulations [8] i.e. the total horizontal seismic force according to the expression:

$$S = KQ = K_o K_s K_d K_p Q \qquad (9)$$

Where: $K_o=1$, $K_s=0,1$, $K_p=1$, and $K_d=0,7/T$.

For the frame presented in Fig.10 for the various degrees of fixation of individual members in the nodes (table 1.) circular frequencies and periods of oscillation of free horizontal oscillations of the frame have been calculated as well as horizontal seismic forces according to the Regulations [8] and the maximum horizontal displacement of the frame pursuant to the article 16 of the Regulations ($u_{1s}^{(i)} \leq H/600$, H- height of the structure in cm). The frame is treated as a reinforced-concrete one with cross-section dimensions determined by designing the structure to withstand influence due to evenly distributed load q=20kN/m and concentrated force in the node 2 of 40kN (Fig.10.) under the provision that the failure occurs in reinforcement. The following dimensions of cross sections have been obtained: for the members 1 and 2 b/h=50/115cm, and for the member 3 b/h=50/90cm. Modulus of elasticity of concrete is determined according to the Regulations BAB87 and for the adopted grade of concrete MB30 amounts to E=3150·10^4kN/m^2, thus the comparative rigidity to bending of the frame (member 3) EI=1746937,5 kN/m^2, the weight of the structure is

Q=ql=20·25=500 kN. Circular frequencies of the frame are determined according to the expression:

$$\omega^i = \sqrt{\frac{1}{mu_1^i}} = \sqrt{\frac{gEI}{QEIu_1^i}} \tag{10}$$

Where :

ω^i - is the circular frequency of free oscillations of the frame (i= a to f)

g – gravitational acceleration

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

Table 2.

	EI u_1[m]	ω[s^{-1}]	T[s]	K_d=0.7/T	$K_{d,usv}$	S[kN]	$u_{1,s}$[m]
a	149.00	11.22	0.539	1.251	1,0	50.00	0.0077
b	229.91	9.036	0.694	1.007	1.0	50.00	0.0120
c	383.26	6.998	0.897	0.780	0.780	39.00	0.0156
d	402.25	6.830	0.919	0.760	0.760	38.00	0.0159
e	505.70	6.093	1.030	0.679	0.679	33.95	0.0179
f	633.27	5.445	1.153	0.607	0.607	30.35	0.0201

CONCLUSION

The structures with semi-rigid joints are those systems where the connections of the members in nodes are not absolutely rigid, but permit, in the general case, a certain degree of relative displacement in the directions of all generalized displacements. In the present day engineering practice, in design of the structure, this fact has been marginally taken into consideration, if at all. If the influence of semi-rigid connections is underestimated, and if they are treated as joints this has negative effects on the cost-efficiency of the structure. If an unrealistically high degree of fixation of members in nodes is assumed, the obtained results do not favor safety, which may have negative effects on bearing capacity, durability and stability of the structure.

Dynamic structural tests defines the actual dynamic characteristics of the structures, that is, resonant frequencies of primary tones in horizontal and vertical load, forms of vibrations in these frequencies as well as the corresponding coefficients of viscous damping. All these parameters represent a starting point for any mathematical modeling of the structure, and as the analytic researches have been conducted and processed, performing a reanalysis is facilitated with a far greater precision that it was possible in the design phase. The test is conducted on a pure frame structure with no façade walls.

Experimental research of dynamic characteristics of standardized prefabricated structure „MINOMA-2“ and „MINOMA-3“ have been carried out applying the following types of experiments:

1) Experiments with forced harmonic excitation,
2) Experiments with free oscillations,
3) Experiments with ambient oscillations.

Regarding the scarce data in the national and world literature about the periodic and damping force (expressed by the percentage of viscous damping) for the considered standardized prefabricated structures, the obtained results represent the basic values in analysis of strong earthquake soil movements and evaluation of overall seismic safety. The matrix form as a method of structural analysis, and especially the finite element method (FEM) in the recent period, have found wide application in dynamic structural analysis in various areas of design engineering.

Therefore, numerical methods, used for obtaining the approximate solutions in the structural dynamics have a special importance. It has been demonstrated that the existing software packages can be adopted for calculation of structures with semi-rigid connections of members in nodes. On the presented numerical examples under dynamic (seismic) load, the basic dynamic characteristics, displacements, seismic forces differ considerably depending on the degree of fixation of the members in the nodes of the structure. This unequivocally indicates that the actual rigidity of connections must be adequately taken into consideration while designing all engineering structures.

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