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SEISMIC RESPONSE OF RC INFILLED FRAMES - MICRO-MODEL FOR NON-LINEAR NUMERICAL SIMULATION

Lidija KRSTEVSKA[1] and Danilo RISTIC[2]

SUMMARY

Presented here is the developed analytical micro-model for refined simulation of the non-linear behavior of RC infilled frames under strong earthquakes. The concept is based on discretization of the structural system by a finite number of nonlinear discrete components connected at the nodal points of the model and knowledge of the stress-strain relationship for each material in the structure (micro-modeling concept). The discrete components are different for the individual structural elements of the system, their main characteristic being nonlinearity. The application of the proposed concept applying the nonlinear discrete components and using the originally developed complex computer program *EURO NORA* is performed by modeling and seismic analysis of a plane RC frame model with masonry infill. The verification of the proposed analytical models is presented using the obtained results from shaking table tests on a two storey-two bay model of the plane frame. Selected results obtained by the dynamic analysis of the analytical micro model are presented trough time histories and hysteretic relationships of the important response parameters. The results obtained from the extensive theoretical studies confirmed the applicability of the proposed micro-models for refined non-linear numerical simulation of the seismic response of reinforced concrete frames with masonry infills under strong earthquakes.

INTRODUCTION

The presence and the popularity of frame systems with infill has been the reason for the performance of numerous experimental and analytical investigations of their characteristics and behaviour under the effect of different kinds of loads for the last fifty years, which has been initiated by the not so small number of damaged and ruined frame structures during strong earthquakes. A lot of experiments on the masonry used as an infill have been done in the laboratories of many world institutions dealing with scientific-research work. Masonry as an infill is used in a great number of different variants in respect to the type of bricks, type of mortar, presence of reinforcement in the masonry, way of loading and alike. Following the scientific-research trends in Europe and in the world in the field of earthquake engineering and stability of systems, noteworthy is the considerable number of cooperative projects that involve research teams from a

[1] Assistant Professor, Institute of Earthquake Engineering and Engineering Seismology, Skopje, Republic of Macedonia. Email: lidija@pluto.iziis.ukim.edu.mk
[2] Professor, Institute of Earthquake Engineering and Engineering Seismology, Skopje, Republic of Macedonia. Email: danilo@pluto.iziis.ukim.edu.mk

number of countries and treat structural systems with masonry infill from different aspects. Within the frames of such an international cooperative project INCO COPERNICUS PROJECT No. IC15-CT97-0203, "TOWARDS EUROPEAN INTEGRATION IN SEISMIC DESIGN AND UPGRADING OF BUILDING STRUCTURES", realized in the period October 1997 - January 2001, financed by the European Commission, complex investigation of reinforced-concrete frame structures with masonry infill has been performed from several aspects, by participation from seven renowned European institutions: University of Ljubljana, Slovenia, University in Bucharest, Romania, Institute for Structures and Architecture, Slovakia, ISMES, Bergamo, Italy, University in Bristol, Great Bretain, JRC, Ispra, Italy and Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Skopje, Republic of Macedonia . The research activities within the project related to refined nonlinear numerical simulation of RC frames with infill have successfully been realized in IZIIS, Skopje, Republic of Macedonia. A new concept for nonlinear refined micro analysis of frame structures with infill of non-reinforced and reinforced masonry, with or without openings for doors or windows has been proposed. The verification of the applied analytical procedure through determination of the nonlinear response of these systems to earthquake effect showed that the nonlinear response of frame systems with masonry infill can successfully be simulated by use of the proposed concept for refined nonlinear micro-modeling and by application of the developed EURO NORA programme.

PROPOSED CONCEPT OF NONLINEAR MICRO-ANALYSIS BASED ON PHENOMENOLOGICAL MODELS OF DISCRETE COMPONENTS

General Approach

The proposed concept of nonlinear analytical micro-modeling of reinforced-concrete frames with masonry infill is based on discretization of the structural system by a finite number of nonlinear discrete components (NDC-nonlinear discrete components) connected at the nodal points of the model (NP - nodal points). The concept itself is based on knowledge of the σ–ε relationship for each material incorporated in the structure, i.e., the material from which the structural elements are made (micro-modeling concept). The discrete components are different for the individual structural elements of the system, their main characteristic being nonlinearity. For micro-modeling of an integral RC frame system with masonry infill, corresponding models of nonlinear discrete components (NDC-models) have been developed to represent the specific nonlinear characteristics of the different structural elements and materials of the system. More concretely, the following four different types of NDC models that were further implemented in the micro-modeling concept of frame system with infill, have been developed:

1. *NDC-FRAME* model - nonlinear model of discrete components for the beam elements, for nonlinear modeling of the behaviour of the structural elements of the frame - the columns and the beams;
2. *NDC-INFILL* model - nonlinear model of discrete components for modeling of the infill elements;
3. *NDC-MORTAR* model - nonlinear model of discrete components for modeling of behaviour of mortar in all the contact zones;
4. *NDC-REINFO* model - nonlinear element for modeling of the behaviour of reinforcement, in the case of reinforced masonry.

Phenomenological Models of Discrete Components - NDC Models

NDC-FRAME Model

To model the nonlinear behaviour of structural reinforced concrete or steel elements of the structure, the developed micro-nonlinear finite element presented in Fig. 1. is used. This model has originally been developed and proposed by Prof. Dr. Danilo Ristic and has multiply been applied and verified based on the results from numerous experimental tests.

The 2D element is defined at two nodal points i and j that have three global degrees of freedom each: axial deformation and two rotations at the ends. The inner forces and the forces at the ends are related to the adopted referent axis of the element, defined by nodal points *i* and *j*, while the external forces act upon the nodal points of the element in the direction of the global degrees of freedom of the node.

The distribution of nonlinearity along the finite element is controlled by a finite number of sub-elements defined between previously specified cross-sections - interface elements. The main purpose of these interface elements is computation and including of nonlinearity and its propagation along the element depending on the previous loading history and the current level of axial force. Defined for each interface element are: a) axial stiffness-stress-strain (σ–ε) relationship with included characteristic parameters, and b) bending stiffness-moment-curvature (M–φ) relationship providing thus realistic simulation of the nonlinear behaviour of the element during quasi-static or dynamic effect. The interface element has two local degrees of freedom: axial deformation ε_{as} at the plastic center of gravity of the cross-section and curvature φ_s of the cross-section. Each interface element is divided into layers-axial surfaces and for each layer are defined the hysteretic stress-strain (σ–ε) relationships.

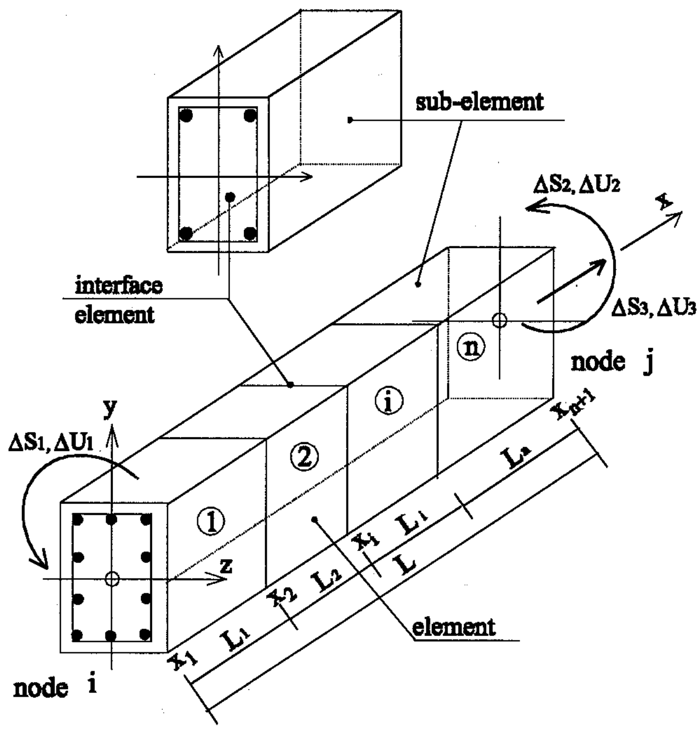


Fig. 1. Finite element, NDC-FRAME model

NDC-INFILL Model

Refined nonlinear modeling by discrete components of structural infill elements is achieved through the infill unit (modulus) composed of six axial nonlinear springs or nonlinear discrete components, Figure 2. By successful analytical presentation of the realistic nonlinear hysteretic relations for each separate discrete component, the characteristics of nonlinear behavior and the failure modes of the infill under cyclic load effect can realistically be simulated.

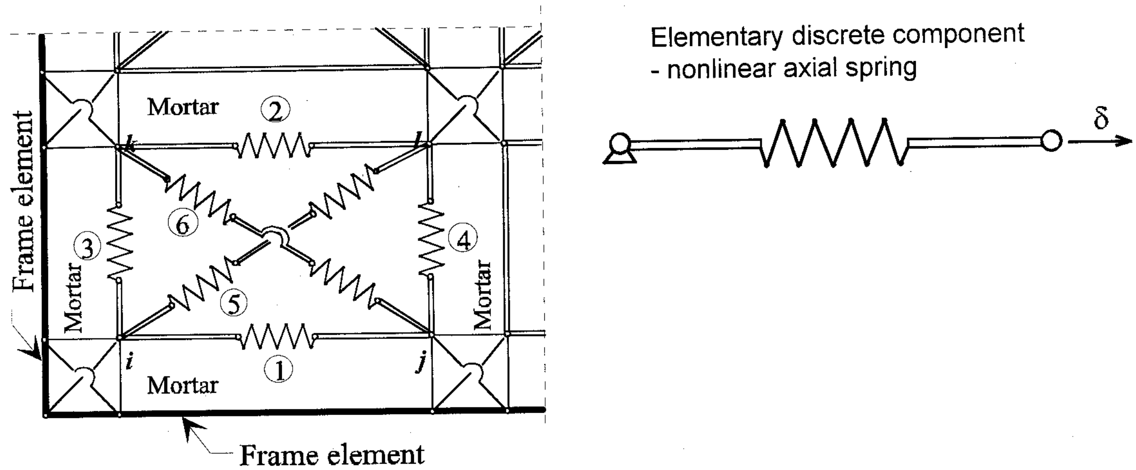


Fig. 2. NDC-INFILL model - "brick modulus" formed by six discrete components, axial nonlinear springs

NDC -MORTAR Model

Analogously, refined nonlinear modeling by discrete components of mortar elements is achieved through a similarly assembled nonlinear mortar unit whose standard shape consists of six equivalent nonlinear discrete components-axial springs, presented in Fig.3.

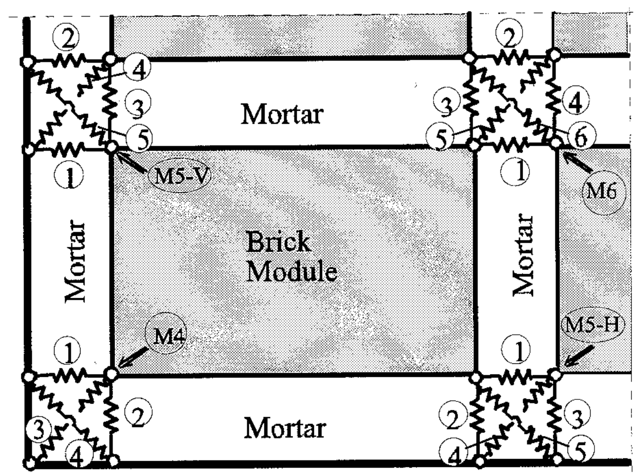


Fig. 3. NDC-MORTAR model, discrete components of nonlinear axial springs

Adopting a successful analytical presentation of actual nonlinear hysteretic relations for each discrete component also in this case, the characteristics of inelastic behavior and failure modes of mortar under the effect of generalized cyclic loads can also be realistically simulated.

NDC-REINFO Model

With this discrete nonlinear element, modeling of the nonlinear behaviour of the infill reinforcement is done, should there is a case of reinforced masonry. In accordance with the introduced analytical approach to nonlinear micro-modeling, the proposed nonlinear model for the reinforcement elements placed in masonry consists of a nonlinear discrete component - axial spring with adopted characteristic nonlinear axial force-deformation (P-δ) relationship, Fig. 4.

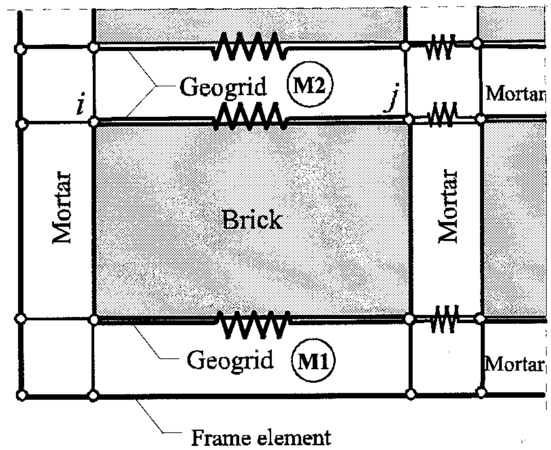


Fig. 4. NDC-REINFO model, for modeling of reinforcement in case of reinforced masonry

By appropriately adopted analytical presentation of the current nonlinear hysteretic relationship, a realistic simulation of inelastic behaviour of reinforcement layers under earthquake or other cyclic effect is provided for each discrete component.

The nonlinear stiffness matrix of the discrete components for the INFILL and MORTAR models as well as the REINFO model is composed in compliance with the finite element method concept and is used further as such in assembling the total tangential stiffness matrix of the integral system for the considered step of the solution, which is constant in the course of the discrete time interval Δt.

COMPUTER PROGRAMME *EURO-NORA* FOR NONLINEAR ANALYSIS OF RC FRAME STRUCTURES WITH MASONRY INFILL, BASED ON THE MICRO-MODELING CONCEPT

To implement the concept of micro modeling in the analysis of nonlinear response of structures, an optimized analytical procedure was developed which can be summarized into the following steps:

- idealization of the system with nonlinear infill components and frame elements;
- identification of unknown displacements at the nodes by which the displacement response of the idealized structure is completely defined;
- derivation of equations of equilibrium of forces corresponding to the nodal displacements;
- solving of the equilibrium equations over unknown displacements and
- computation of stresses in elements or distribution of forces using the known nodal displacements.

For structural analysis with application of the proposed micro-modeling concept, a computer programme EURO-NORA was developed by Prof. Dr. Danilo Ristic (2001). This programme offers the possibility for performance of the following three types of analysis:

- static linear and nonlinear step-by-step analysis (under time-dependent loads);
- analysis of initial dynamic characteristics;
- dynamic linear or nonlinear step-by-step analysis (time-history response).

EURO-NORA involves ten different options for analysis, presented in the flow chart in Fig. 5. While performing dynamic analysis of a structure under earthquake effect of different intensity, the external load (the earthquake) is applied through a time history of acceleration assigned by discrete values specified at equal time steps. The current version of the programme is designed for analysis of two-dimensional structures, while during the execution of the programme, a great number of files are used. In these files, there is elimination of certain variables as well as temporary storing of time dependent parameters that are defined in the step-by-step solving process. The efficiency of solving has been achieved by processing and eliminating of all the matrices in compact form, through application of half-band matrices. The constant matrices of the structure are first formed, while the nonlinearities are taken into account only in the step-by-step solving process.

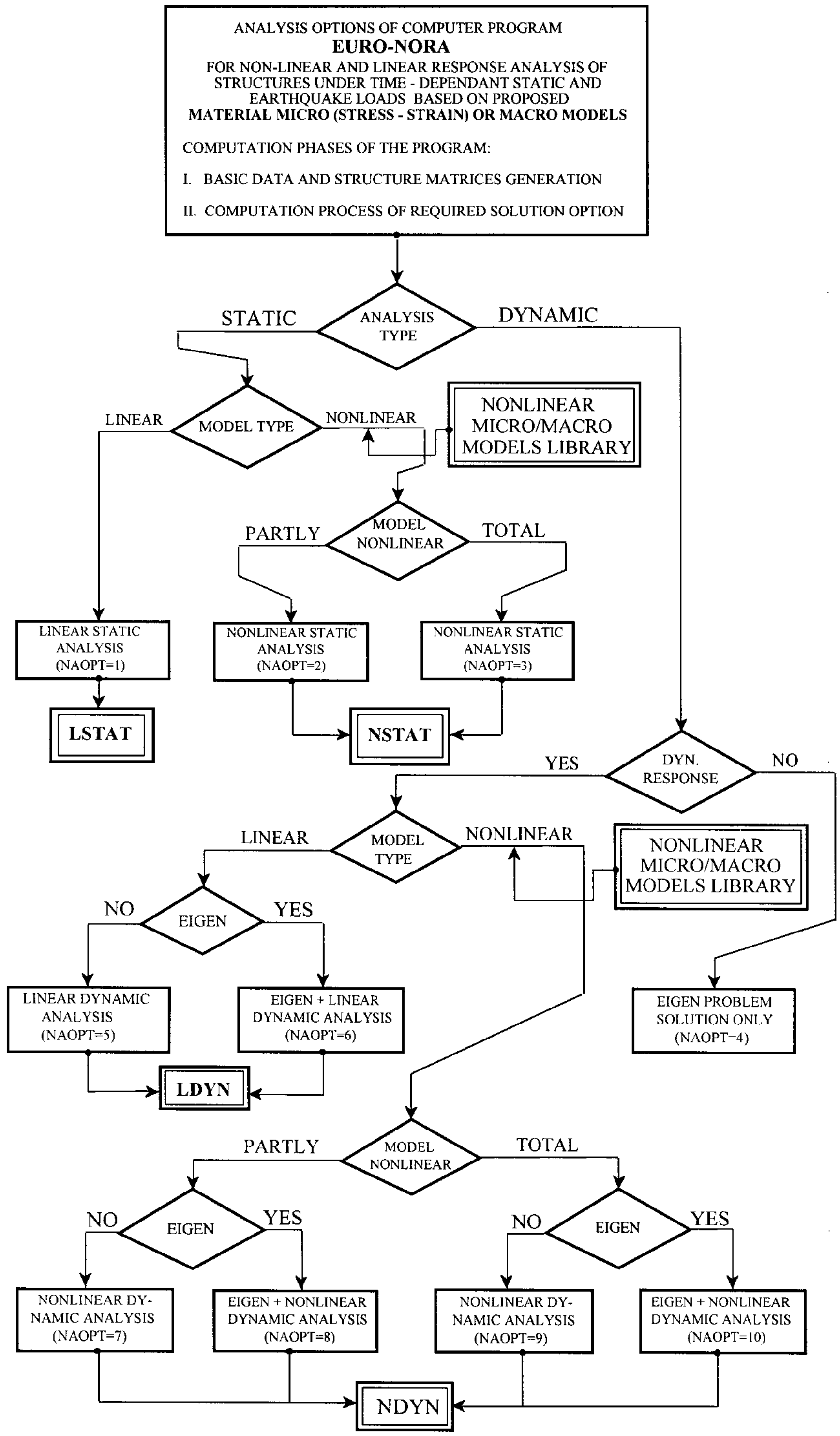


Fig. 5. Flow-chart of computer programme EURO-NORA with the options for analysis

NONLINEAR MICRO-MODEL OF RC FRAME WITH INFILL

To verify the practical application of the formulated nonlinear micro-model for real numerical simulation of nonlinear behaviour of RC frame structures with masonry infill under earthquake excitation, modeling and seismic analysis of two different plane frame models with masonry infill tested experimentaly in laboratory conditions have been performed. The example presented in this paper is related to a two-storey two-bay RC infilled frame (tested experimentaly in the Laboratory of ZRMK in Ljubljana, Slovenia) which is a part of the spatial frame model tested in the Laboratory of the University in Bristol, UK, designed and constructed to a scale of 1:4, Fig. 6, according to the true replica modeling technique.

The physical model is an RC frame infilled with plain masonry without openings. The spatial frame model has been tested on the seismic shaking table in Bristol applying uniaxial excitation of modified sine type in the frames of a common envelope.

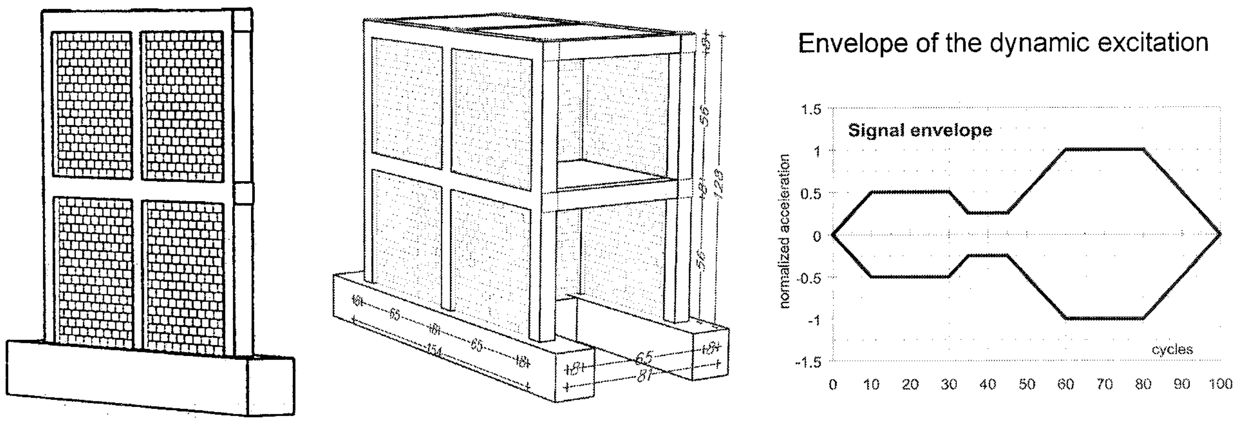


Fig. 6. Plane and spatial infilled frame models tested dynamically

Table 1. Transformation of some measured model quantities in prototype quantities according to scaling factors (during the test with which the analytical results have been compared later)

parameter	model (1:4)	scaling factor	prototype
max. diagonal deformation in infill	2.52 ‰	1	2.52 ‰
max. drift	0.78 ‰	1	0.78 ‰
max. acceleration at the top	6.02 g	1	6.02 g
the second period	0.065 s	2	0.13 s

Formulated analytical micro-model

Applying the proposed micro-modeling concept, the analytical model for the two storey infilled frame is formulated as presented in Fig. 7. The analyses are performed for nonlinear analytical model for the prototype of the scaled model, having the following global geometry: Lp=5.84m and Hp=5.12m.

According to the proposed micro-modeling concept, the analytical model has the following characteristics:

- total number of nodal points NP=729
- total number of boundary nodes NBN=27
- total number of degrees of freedom NDOF=2106

- total number of basic nonlinear elements NEL-B=2058
- total number of dummy elements NEL-D=2058
- total number of all discrete elements NEL-TOT=4116
- total number of frame elements NFEL=130
- total number of brick elements NBEL=864
- total number of mortar elements NMEL=1064
- final number of used hysteretic relations NHYS=5936

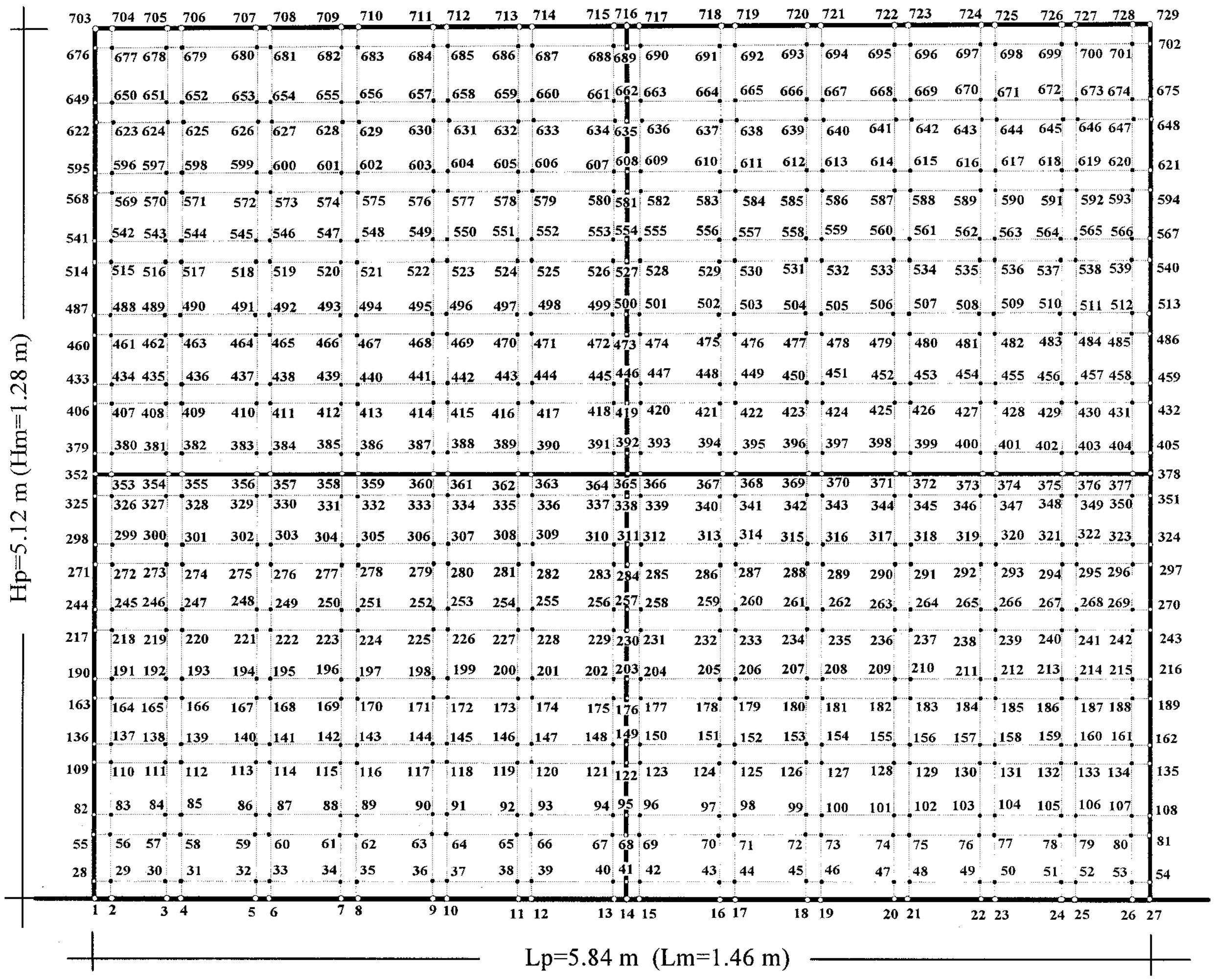


Fig. 7 Analytical model of nonlinear discrete components for the model of the frame tested on seismic shaking table in Bristol, UK

Table 2 summarizes the applied hysteretic relationships for the NDC models of the analytical model with their defining parameters.

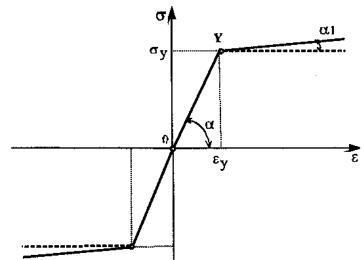
Analysis of the analytical model

First of all, the mode shapes of the analytical model have been obtained:

a) first mode shape: T1=0.078s f1=12.8Hz
b) second mode shape: T2=0.030s f2=33.3Hz
c) third mode shape: T3=0.029s f3=34.5Hz
d) forth mode shape: T4=0.025s f4=40.0Hz

Table 2. Rewiev of the applied hysteretic models and their parameters

<table>
<tr><th>Element</th><th>Applied model and model parameters</th></tr>
<tr><td rowspan="2">Frame elements</td><td>Bi-linear model (σ–ε) with 3 parameters for simulation of the axial stifness of the interface elements

$E = tg\ \alpha = 10750000$ kN/m^2
$\sigma_y = 13150$ kN/m^2
$\Delta = \alpha_1 / \alpha = 0.05$

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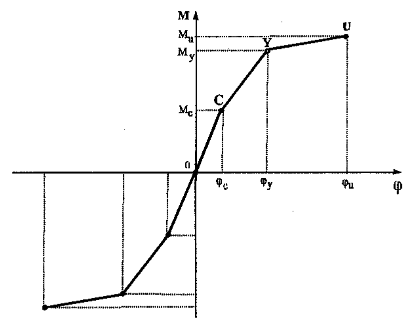
<tr><td>Takeda model (M–φ) with 8 parameters for simulation of the bending stifness of the interface elements

M_c=400.0 kNm , φ_c=0.0025
M_y=700.0 kNm , φ_y=0.006
M_u=740.0 kNm , φ_u=0.02

-N_x=-2000000 kN, N_x=2000000 kN

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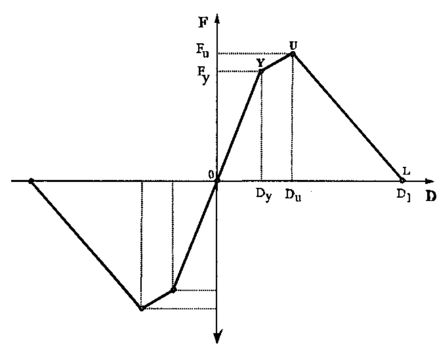
<tr><td>Infill elements</td><td>Infill model with 5 parameters for simulation of axial compression and tension

F_y = 118.58 kN , D_y = 0.001070 m
F_u = 148.2 kN , D_u = 0.001604 m
F_l = 0.0 kN, D_l = 0.004278 m

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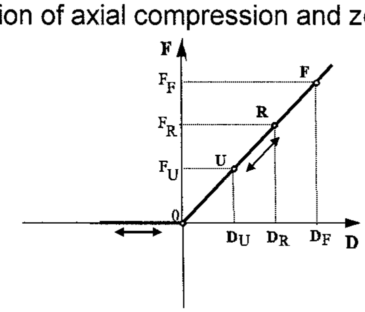
<tr><td>Mortar elements</td><td>model MOR-M2, with 7 parameters for simulation of axial compression and zero tension

D_m = 0.0 kN
D_u = 0.000121 m F_u = 105.856 kN
D_R = 0.000182 m F_R = 158.784 kN
D_F = 0.000242 m F_F = 211.712 kN

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The seismic analysis for the model is performed under the same dynamic excitation like the one applied during the experimental testing of the model on the seismic shaking table at the University in Bristol. The analysis was performed applying a solution time step of $\Delta t=0.001s$ and a total time solution time T=10s.

The maximum input intensity was Amax=1.5g, as an intensity which caused serious damage to the physical model during the experimental testing and the period of the input sine type function was equal to the first period of the model prototype, T_{sin}=0.080sec in order to produce vibration of the model in resonance conditions in the initial state.

Selected results obtained by the analysis of the model M2-P are presented in Fig. 8 to 10.

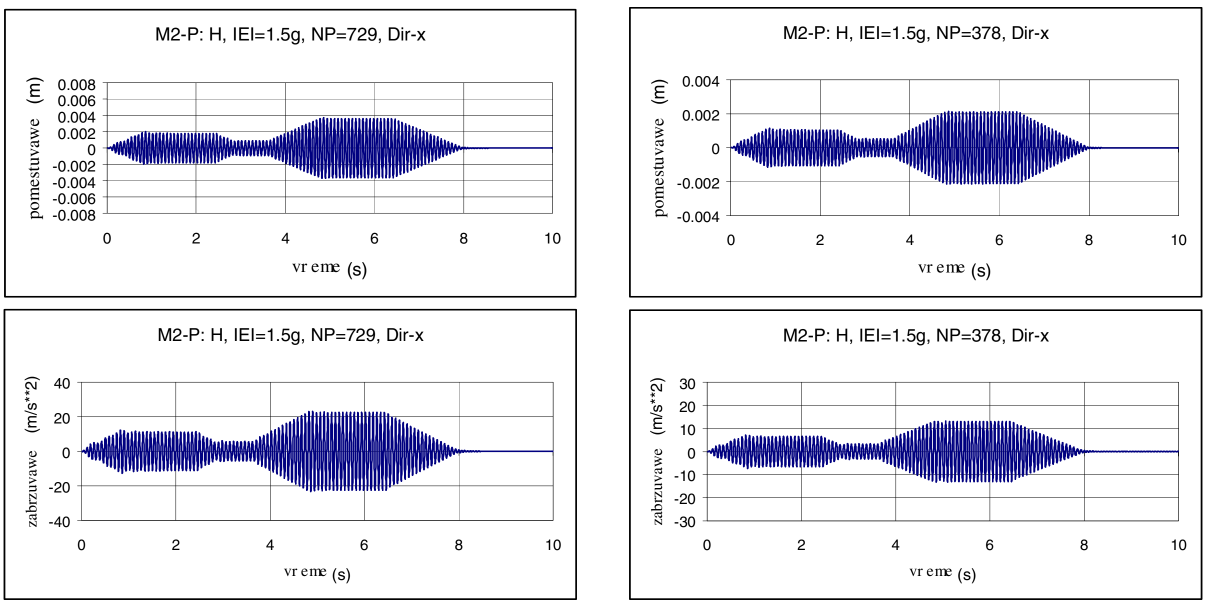


Fig. 8. Displacement and acceleration response in x-direction for the model, nodal points NP=729 and NP=378

Fig. 9. Hysteretic relationship force-displacement in x-direction, EL=78, NP=729 and EL=65, NP=378 for the model

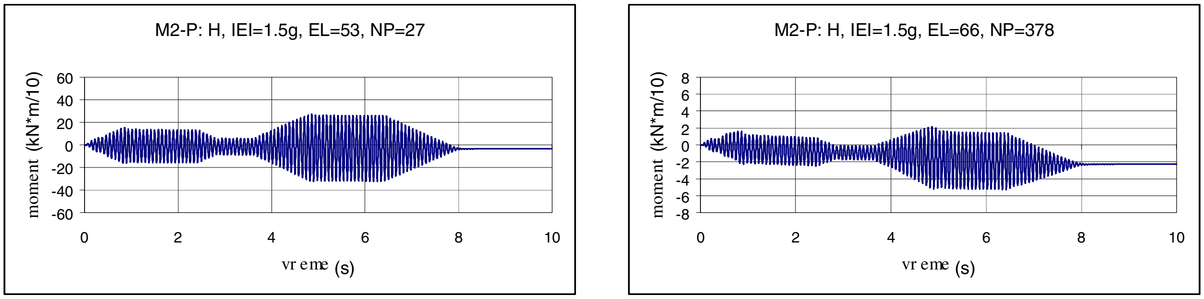


Fig. 10. Moment time history, EL=53, NP=27 and EL=66, NP=378

Some characteristic diagrams of selected parameters at the moment of the maximal displacement during the dynamic action are presented in Fig. 11 and 12.

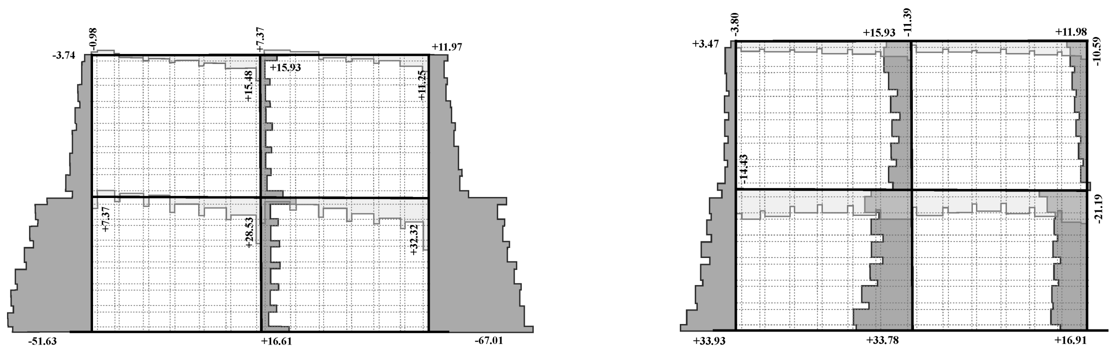
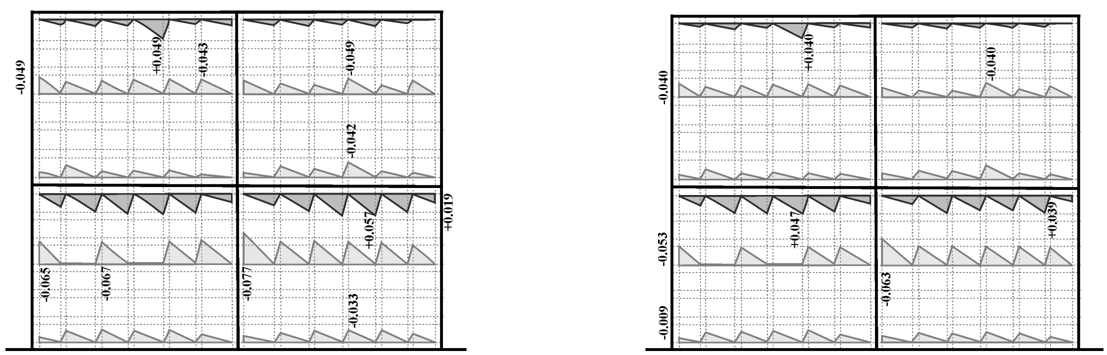


Fig. 11. Axial and transverzal forces (in kN/10) for the model at the moment of max. displacement

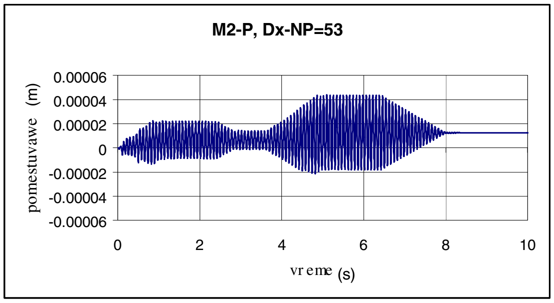


a) *b)*

Fig. 12. Force distribution (in kN/10) in the nodal points at the brick-mortar contact in the horizontal layers of the mortar for the model for d_{max} a) forces in X-direction, b) forces in Y-direction

Presented diagrams of shear and axial forces (Fig. 11) calculated in the elements of the NDC-FRAME models (frame elements, columns and beams) have the expected distribution for a frame system under lateral force action. For the maximal deformation of the system during the dynamic excitation, d_{max}=3.73mm in NP=729, the higher values of shear and axial forces at the first storey are obvious. This storey has been much more damaged then the second storey.

An interesting parameter showing the possibilities of the applied computer program for performing a complex nonlinear analysis of a system modeled applying the proposed micro-modeling concept is displacement of the brick-mortar contact nodal point in the right bottom corner, NP=53, Fig. 13. In this area, high compression forces and crashing of mortar is expected. After the dynamic action, the nonlinear displacement for this point in both directions is obvious.



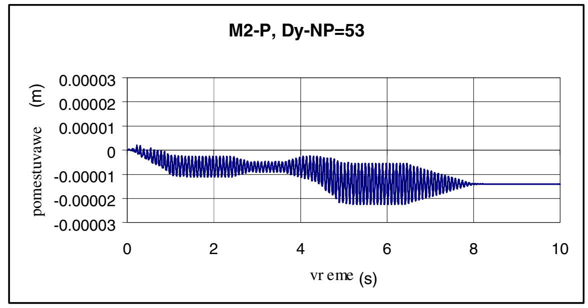


Fig. 13. Time history of displacement for nodal point NP=53 in x and y direction

In Table 3, a review of the most important quantities of the physical model tested experimentally, as well as the corresponding prototype and analytical model of this prototype is given. The difference in the first period of the models is 6.6%, which indicates that the initial stiffness is quite correctly simulated. In the dynamic response parameters – accelerations and displacements, there are differences which indicate that the analytical model has not been excited to vibrate in a notable nonlinear state, even though some nonlinearity is evident.

Table 3. Characteristic parameters for the considered types of two storey frame

Model type	T_i (s)	f (Hz)	f_i (Hz)	a_i (g)	a_1 (g)	a_2 (g)	D_1 (mm)	D_2 (mm)	DAF
Physical 1:4	0.042	24.0	21.0	1.0	2.6	4.0	0.85	0.6	4.0
Physical prototype	0.083	12.0	10.5	1.0	2.6	4.0	3.4	2.4	4.0
Analytical micro-model	0.078	12.8	12.5	1.5	1.3	2.3	2.09	3.73	1.57

T_i – initial natural period of the model

f – initial natural frequency of the model

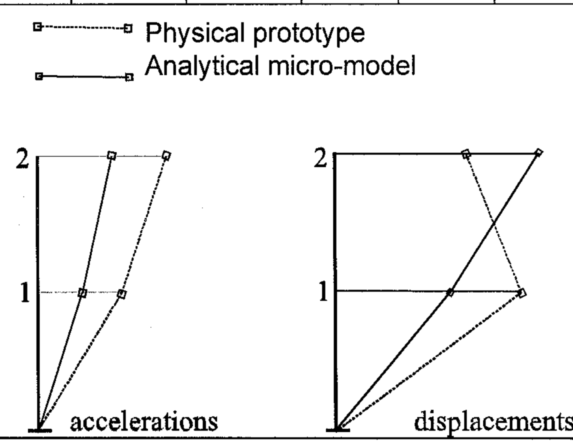
f_i – excitation frequency

a_i – input acceleration

a_1, a_2 – first and second storey accelerations

D_1, D_2 – first and second storey displacements

DAF – dynamic amplification factor



THE MOST IMPORTANT CONCLUSIONS

Based on the performed investigations, the following important conclusions were drawn:

- the proposed concept of micro-modeling has a lot of advantages since it enables detailed simulation of the characteristics of the nonlinear response of the integral system of masonry infill frames;
- the concept has unique advantages since it enables realistic simulation of a complex asymmetric hysteretic response of the frame under the effect of variable dynamic axial forces;
- the characteristics of the infill components include simulation of opening of cracks, closing of cracks, failure under tension, failure under compression, modeling of contact brick-mortar, mortar – column contacts, mortar - beams contacts, combined contacts, etc., and
- the concept has a lot of advantages since it enables modeling of ordinary infill, infill with openings, non-strengthened infill, strengthened infill, different types of infill, etc.
- Finally, based on the proved successfulness of the originally developed computer programme EURO-NORA and the successfulness of the presented theoretical results, it was proved that the developed concept of a micro-model possesses theoretical generality and extraordinary preciseness. Considering the offered advantages, the proposed concept of a nonlinear micro-model (NDC Model) is expected to be widely applied in modern earthquake engineering.

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