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SAFETY STAIRCASE FOR EVACUATION . A METHOD OF RESCUING FROM NON-SEISMIC BUILDING IN EXTRAORDINARY SITUATIONS .

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SUMMARY

It's proposed an engineering solution of safety staircase for evacuation in a form of space precast reinforced concrete structure . Proposed safety staircase is an independent structure and isn't connected structurally with existing building . Pass from existing building to safety staircase is carried out by means of sliding platforms – bridges. Series of structural FEM analysis were performed for connection joints : characteristics of joint rigidity (or joint flexibility parameters) and limits of load - carrying capacities of joints were estimated . Structural design drawings for proposed structure of the staircase were elaborated for variants with various number of stories , according to results of series of performed structural analysis.

It looks, that important advantages of proposed engineering solution are : possibilities of disassembling and repeated use , using of the staircase as a fire resisting , life - saving staircase after an earthquake event , protective structure in case of military attack condition.

1. INTRODUCTION

It looks to be right , to strengthen existing non-seismic buildings according to corresponding and well known standards and methods for seismic strengthening . But practically , there is a lot of such buildings for which strengthening is difficult by several reasons (limits of budget, complicacy of work execution and so on) . On another hand, new type information systems for urgent situations – so named , " early warning systems " , were elaborated and are used last decades . Using of such systems allow to have time 20 -30 sec for urgent evacuation of residents . In many cases , it's not safety or impossible to use existing staircases of non- seismic buildings for evacuation during these 20 -30 sec .

It's proposed an engineering solution of safety staircase for evacuation in a form of space precast reinforced concrete structure . Proposed safety staircase is an independent structure and isn't connected structurally with existing building . Pass from existing building to safety staircase is carried out by means of sliding platforms – bridges. Series of structural FEM analysis were performed for connection joints : characteristics of joint rigidity (or joint flexibility parameters) and limits of load –

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carrying capacities of joints were estimated . Structural design drawings for proposed structure of the staircase were elaborated for variants with various number of stories , according to results of series of performed structural analysis.

It looks , that important advantages of proposed engineering solution are : possibilities of disassembling and repeated use , using of the staircase as a fire resisting , life - saving staircase after an earthquake event , protective structure in case of military attack condition.

2. DESCRIPTION OF PROPOSED STRUCTURE

The structure consists of a foundation plate, several space precast one - story sections (parts), and roof plate , which are assembled one by one by height using bolt connections on a building site . External dimensions of the staircase structure in a plan - 3.85 x 6.90 m ; height of one section - 3.0 – 3.5 m. Plan views and elevation of staircase structure are presented on Fig. 1. Space sections and roof plate are of reinforced concrete – thickness – 20 cm , concrete class- B - 40 or B - 50. Internal platforms and local internal stars are of concrete also ; thickness – 15cm , class of concrete - B 40. Space sections, roof plate, internal platforms and stairs are of precast type and are produced at precast concrete plants. Weight of one story section is about 60 t . Sizes and weight of a space section allow to transport it to a place of assembling by semi-trailer. Neighbour sections are assembling by height one by one using special type connections.

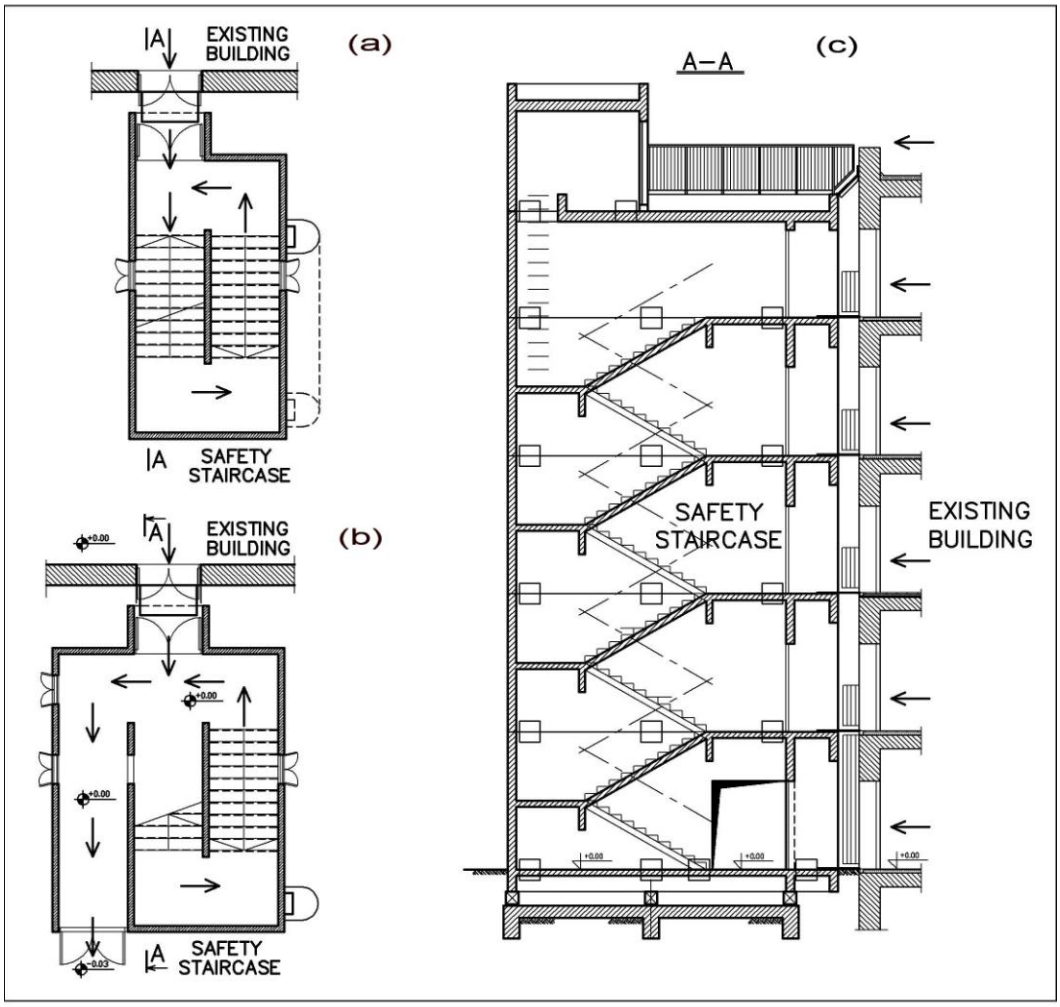

Figure 1. Proposed safety staircase for evacuation :
a - typical story plan ; b - 1-st story plan ; c - elevation view – section – A-A

Typical connection joint is presented on a Fig.2 . It consists of 2 box type details (one at top and one at bottom neighbour precast sections) embedded in r/concrete walls , 2 side plates and 6 bolts M 24 .Similar type connections are used to connect the bottom and top space sections to a foundation and roof plates .

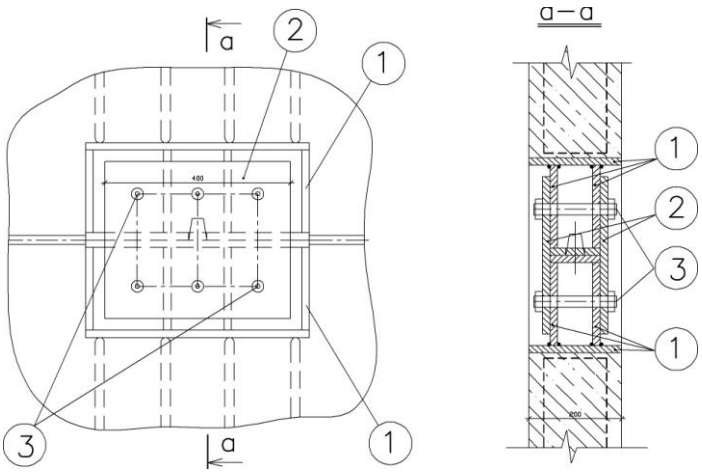

Figure 2. Connection joint :
1 - box type detail , embedded in a reinforced concrete wall ; 2 - patch (side cover) plate ;
3 - connection bolts .

Foundation of the staircase structure is designed as a ribbed mat plate. Class of concrete - B40. Variants of pile type foundations are proposed in cases of high seismic loads . Special type devices could be used to reduce loads transferred to foundations structures . Roof structure is designed as a reinforced concrete monolith plate ; it was analysed for special extra loads due failure of parts from failing of a neighbour building, in situations ,when this building is higher, than safety staircase.

Pass from existing building to a safety staircase is carried out in extraordinary situations by means of sliding platforms – bridges . Sliding type steel bridges are located between existing non-seismic building and proposed precast staircase. One edge side of a cross bridge is supported on existing building and is of sliding type ; another edge side is connected to proposed staircase structure by pivots . So, proposed safety staircase isn't connected structurally with existing non- seismic building and is an independent structure. Space between exixting building and proposed safety staircase is about 50 cm .

Architectural part of proposed safety staircase was elaborated taking into account corresponding standards (FEMA 453, FEMA 428, UFC 3-340-02, Birbraer) . Width of internal stairs (165 cm) is satisfacted to limitations of fire staircase for public buildings. Safety staircases proposed to place at side facades of public buildings - opposite to it corridors ; it's the most effective location of safety starcase . So , evacuation by non-seismic staircases is replaced by evacuation using external seismic safe staircases . Process of evacuation of residents (or inhabitants) is designed speciailly to have flow moving in one direction only (Fig.1) . A special additional r/concrete section on a 1-st story allows to have exit from the safety staircase at a distance about 7.5 m from facade of non- seismic existing building. This is important in situations, when parts of collapsed no- seismic building will fail. Safety staircase is equipped with systems of communications, firefighting, alternative exit for evacuation .

Effective use of proposed safety staircase could be reached in cases of periodical training of citizens. It looks, that most effective is to use the proposed structure for public buildings, where inhabitants are awake and could immidiately catch signals of early warning system.

Units of early warning systems are to be installed in existing non-seismic building, it will provide a period of 20 - 30 secionds for immediate evacuation.

Possibilities of disassembling and repeated use, using of the staircase as a fire resisting, life - saving staircase after an earthquake event, protective structure in case of military attacks present

important advantages of proposed solution . Solution of safety staircase is registrated by US patent pending application no.14/071,746 and by Israel patent pending application no.222887.

3. DECISION OF JOINT CONNECTIONS

Type of joint connections are special in reviewing structure . It's well known that vertical joints between vertical surfaces of neighbour wall panels and horizontal joints between horizontal surface of neighbour wall panels and slab are the main type of joint connections . Usually these connections of walls are designed of a large length. Horizontal joints are carrying loads in conditions " bending + compression" , and just for top stories it's possible case, joint connections are in conditions " bending plus tension " . In our case, number of joint connections is limited - 6, s and it location is limited also . So, values of forces in such type joint connections due load combinations (vertical loads plus seismic actions) are high (40 -50 t) are of a reverse direction , significant tension forces are possible.

Among wide information about theoretical and experimental investigations and state of art of design for precast r/c wall joint connections, several works and information looks most interesting : (ACI 550.R-96, Cook and Bloomquist, PEIKKO, Vimmr). It should be mentioned specially, that maximum allowable tension forces for joints presented by " PEIKKO" are reached 80 -100 t , were tested and used in many real objects . Devices with energy absorption also are elaborated (Bora) and could be used in cases of need .

4. ESTIMATION OF RIGIDITY PARAMETERS FOR JOINT CONNECTION BY METHODS OF NUMERICAL (FEM) SIMULATION

In design of precast reinforced concrete structures, it's important to follow realistic values of rigidities for precast elements and joint connections, specially for multi-storey buildings (Naito, (Hofheins, Mettelli, Schulz). A correct estimation of rigidity parameters for joint connection of the reviewing structure is very important too, as number of joints for connection of two neighbour box sections is small – 6 units per story only.

It's well known, that parameter of rigidity **" K "** in a corresponding direction **" i "** is defined as a value of load **" P(i) "**, which should be applied in this direction to lead to a displacement equal to **" u(i) "** in this taken direction . An opposite parameter – named as a flexibility of element $\lambda_{(i)}$ " is defined as:

$$\lambda_{(i)} = 1/K_{(i)} \qquad \textbf{(1)}$$

Flexibility of a connection, consisting of several (n) elements is defined as a sum of partial flexibilities for these elements in a taken direction :

$$\lambda_{(total)} = \lambda_{(1)} + \lambda_{(2)} + \ldots + \lambda_{(3)} \qquad \textbf{(2)}$$

Correspondingly , rigidity **K (total)** of connection for (n) elements is defined as :

$$\mathbf{K\ (total) = 1/\ [\ 1/K(1) + 1/K(2) + \ldots + 1/K(n)\ ]} \qquad \textbf{(3)}$$

It's easy to find , that value of total rigidity of joint connection **K (total**) couldn't be higher, than value of any partial rigidity of elements of a joint . In simple cases , parameters of rigidity and flexibility could be defined just by calculations , in more complicated cases – several numerical and (or) experimental methods are used .

In our case, the main elements of joint connection are :

1) 2 steel box type details (2 groups of welded plates), embedded in reinforced concrete walls ;
2) 2 steel patch (side cover) plates (thickness - 16 mm) ;

3) connection bolts M24 (number of bolts – 6) .

4.1. RIGIDITY PARAMETERS FOR STEEL BOX TYPE DETAIL

Series of structural analyses were performed for box 3 - dimensional finite- element model . Structural FEM model of box type detail consisted of several groups of plane shell type finite elements to describe bottom and top sheet plates, 2 vertical plates(walls) and 4 vertical transverse plates (stiffeners). Special type finite elements ("spring type ") were used to describe interconnections between these plates and supporting conditions (restrains) for box type detail . Main characteristics of used FEM model : number of nodes - 4400 ; number of elements - 4258 ; number of rigidity types – 28 ; number of load cases – 3 .Loads were applied : in horizontal directions (load case 1 - along global axis " X " , load case 2 – along global axis " Y ") to top sheet plate (group of 12 concentrated loads (at zone of assembly key), in vertical direction (along axis " Z ") - in zones of bolt location (group of 3 concentrated loads) . Some series of analyses were performed for various thicknesses and widths of top and bottom plates to estimate influence of asymmetry for cross-section of box type detail . Some results of these analyses are presented on a Fig. 3.

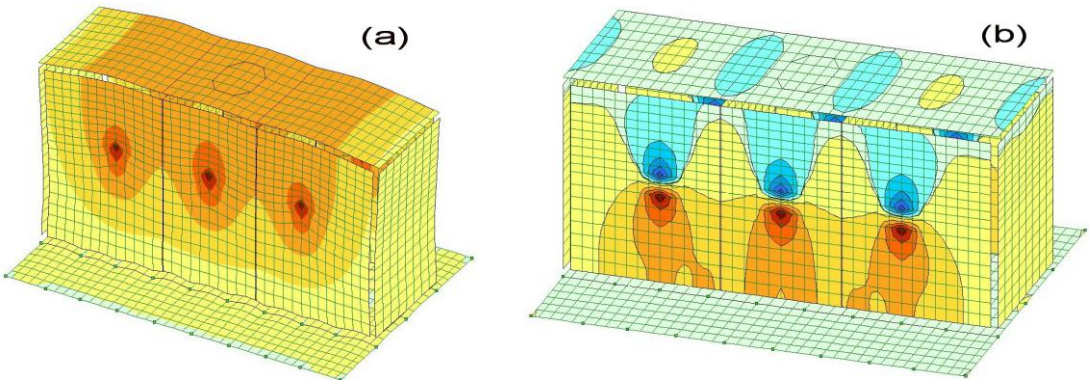

Figure 3. Finite element model of a box type detail :
a – deformed shape : displacement contour along Z , loads in direction Z ; b - normal stress contour for or N(y) , loads in direction Z .

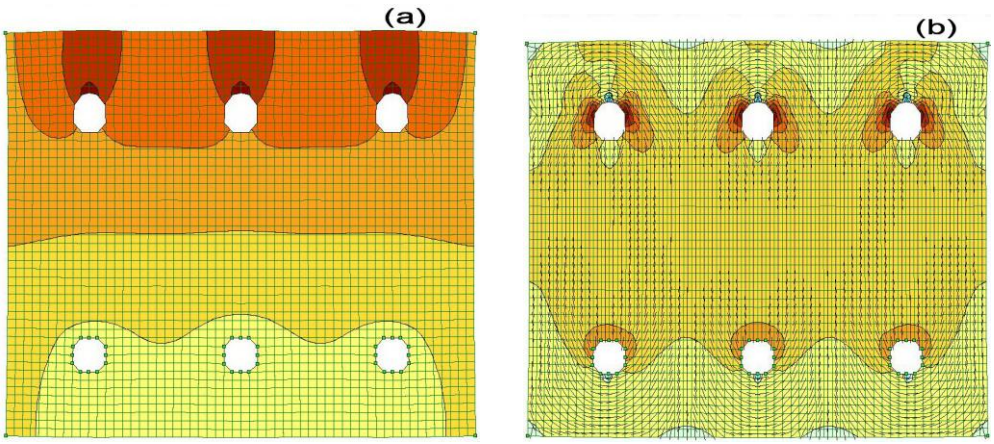

Figure 4. Finite element model of a patch (side cover) plate :
a – deformed shape : displacement contour along Z , loads in direction Z ; b – principal stress contour and trajectories for N(1) , middle layer , loads in direction Z

Following rigidity characteristics of box type detail were found according to results of analysis :

in direction " X " : **K(1,x)** = 3.72 x 1.0E5 t/m **;** $\lambda_{(1,x)}$ = 0.27 x 1.0E-5 m/t ;

in direction " Y " : **K(1,y)** = 0.85 x 1.0E5 t/m ; $\lambda_{(1,y)}$ **)** = 1.18 x 1.0E-5 m/t ;

in direction " Z " : **K(1,z)** = 1.41 x 1.0E6 t/m ; $\lambda_{(1,z)}$ = 0.71 x 1.0E-6 m/t .

4.2. RIGIDITY PARAMETERS FOR PATCH (SIDE COVER) PLATES

Detail structural finite element model of a patch plate consisted of several groups of plane shell type finite elements of triangular and rectangular shape ; special type (" spring type ") finite elements were used to simulate edge conditions . Presence of 6 holes - 3 holes for top and 3 holes for bottom bolts was taken into consideration . Main characteristics of used FEM model : number of nodes - 2940 ; number of elements - 2880 ; number of rigidity types – 7 ; number of load cases – 3. Loads were applied by perimeter of every hole as a group of concentrated forces . Some results of patch plate analysis are presented at Fig. 4 .

Following rigidity characteristics of steel cover plates were estimated according to results of analysis : in direction " Z " : **K(2,z)** = 1.20 x 1.0E6 t/m ; $\lambda_{(2,z)}$ = 0.83 x 1.0E-6 m/t .

4.3. RIGIDITY PARAMETERS FOR A BOLT GROUP

Every two neighbour box type details (embedded in bottom and top reinforced concrete walls) are connected by 6 bolts of diameter 24 mm using 2 patch (side cover) plates . Taking into consideration special type of reviewing structure and it use, it was proposed to use bolts of high strength material (type - Class 8.8 or Class 10.9) , but as <u>non- preloaded</u> <u>ordinary</u> bolts (without it pre-stressing) . Three parallel bolts were represented as an equivalent (by axial and bending rigidities) stick . Structural FEM model consisted of bar type finite elements to describe equivalent stick and special type ("spring type") finite elements to simulate edge conditions. Loads were applied to the model as 2 concentrated forces in a corresponding direction (as reactions from webs of box type detail); presence of side plates was simulated by corresponding edge conditions . Some results of analysis are presented at Fig. 5.

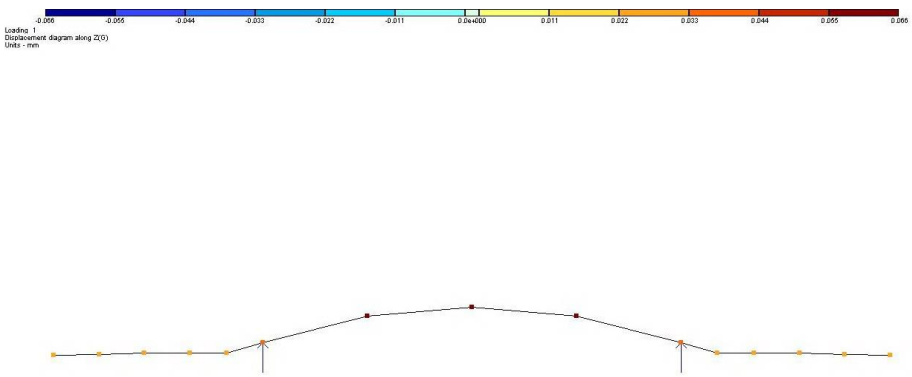

Figure 5. Finite element model of a bolt group :
deformed shape : displacements along Z , loads in direction Z .

Following rigidity characteristics were estimated for a bolt group :

in direction " Z " : **K(3,z)** = 1.56 x 1.0E5 t/m ; $\lambda_{(2,z)}$ = 0.64 x 1.0E-5 m/t .

It should be mentioned, that despite this model looks very simple, results of analysis could be various in a high degree depending of edge conditions . Values of rigidity and flexibility parameters could be differ 5-15 (!) times due to conditions of bolt partial fixing . So, it seems very desirable to estimate rigidity characteristics of these joint connections independently by experiments on fragments of the structure .

According to series of numerical analyses mentioned above, partial rigidities for main parts of the joint connection were estimated ; series of preliminary analyses for stick model of reviewing structure showed, that values of rigidity parameters in direction " Z " are most important and lead to significant changes in results .

So, total flexibility of reviewing joint connection consisting of 2 box type details, 2 side cover plates and 2 groups of bolts in a taken direction " i " could be estimated as :

$$\lambda_{(total,i)} = \lambda_{(1,i)} \times 2 + \lambda_{(2,i)} \times 0.5 + \lambda_{(3,i)} \times 2 \qquad \textbf{(4)}$$

in our case , for example for direction " Z " :

$\lambda_{(total,z)}$ = (0.71 x 2 + 0.83 x 0.5 + 6.40 x 2) x 1.0E-6 = 14.63x1.0E-6 m/t

Corresponding value of rigidity parameter is equal to **K(total ,z)** = $1/\lambda_{(total,z)}$ =
= 1/(14.63x1.0E-6) = 0.68x1.0E5 t/m . Values of **K (total ,x)** and **K (total ,y)** - from 0.50 x 1.0E4 t/m till 1.0 x 1.0E5 t/m were used during series of FEM analysis .

5. USING OF SIMPLIFIED FEM MODELS

Precast reinforced concrete box type sections are assembled using special type bolt connections. Influence of rigidity characteristics of these bolt connections on the main parameters of state for reviewing structure were studied by series of preliminary dynamic structural analyses . Simplified structural " stick type " FEM models were used . Bar type finite elements were used to describe precast box sections, special type (" spring type ") finite elements were used to describe connections. Groups of auxiliary bar elements – " fans " were introduced into a structural model at top and bottom surfaces of every box section ; spring type finite elements are connected corresponding top and bottom " fans " of neighbour box sections. Description of spring type FE element included 6 values of 3 linear and 3 rotation rigidities (in all main directions) . Typical simplified FEM structural model and some results of series of analyses for 6 –story structure are presented on a Fig. 6 .

Firstly, values of these spring rigidity characteristics were taken according to results of several detail structural FEM analysis for all main parts of connections (as described above). Series of simplified analysis were then executed for various values of rigidities (for example , linear rigidity of connection in direction " Z " (by vertical global axis) varied in range from 0.4E4 t/m till 1.0E7 t/m , according to taken proportions of connection details). Analyses were performed for 15 variants for various seismic conditions (by zone seismic factor (Z) and ground categories) and for a number of stories 3 and 6. Maximum linear displacements and periods of free vibrations were the parameters of prior interest (Fig. 6b and Fig.6c).

It was found, that parameters of state for a structure are changed dramatically to compare variants with low and high values of connection rigidity in direction Z : 1-st period of free vibrations increased 2.5 - 4.0 times for 3 - story structure , 2.7 - 5.4 times for 6 - story structure , maximum

horizontal displacements for top of a structure – 5 - 10 (!) times for a variant of 3 stories , 5 -7 (!) times for a variant of 6 stories. Influence of rigidity changes became smaller with increasing of number of stories .

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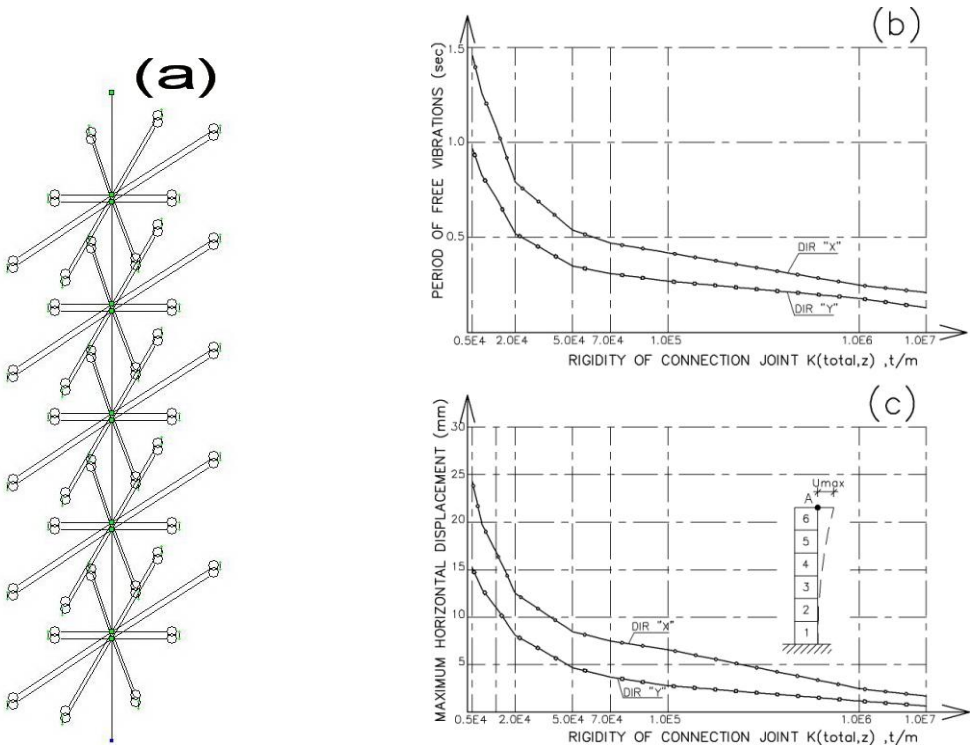

Figure 6. Using of simplified finite element models :
a – structural model , overall view for 6-story structure ; b - relation 1-st period of free vibrations - rigidity **K(total , z)** c - relation horizontal displacements for top level - rigidity **K (total , z)** for seismic loads in directions X and Y ; 6 story structure

6. USING OF FEM MODELS WITH SHELL TYPE FINITE ELEMENTS

Series of FEM analyses were performed for FEM models using shell type finite elements. Structural FEM models consisted of several groups of shell type finite elements to describe walls of box type sections and roof plate. Two types of special finite elements (" spring type ") were used to simulate joint connections between neighbour box sections and supporting conditions (restrains) for bottom box section. So named “ fan “ system – a group of auxiliary bar type finite elements (mass line and fans) was used to transfer seismic loads to a shell type structural model .

Main characteristics of used structural FEM model (6 story structure) : number of nodes - 7760 ; number of elements - 6092 ; number of rigidity types – 23, number of free vibrations modes (3D – modes) - 10 . Some results of these analyses are presented on Fig. 7 .

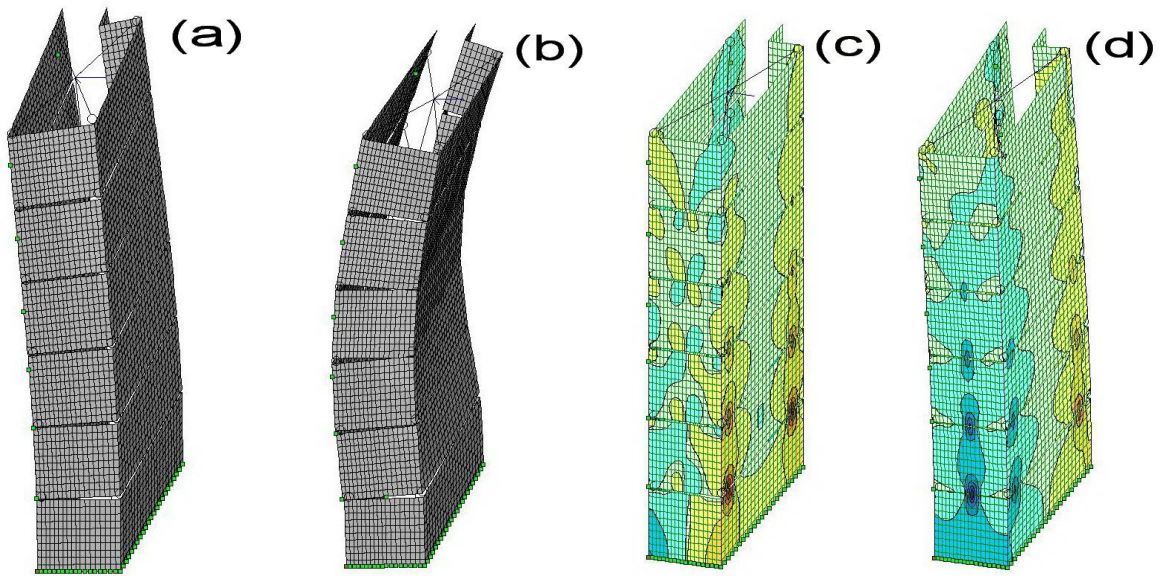

Figure 7. Using of FEM models with shell type finite elements . 6- story structural model : a, b - deformed shape , modes 1 (a) and 2 (b), seismic loads in direction X ; c - normal stress contour N(y), seismic loads in direction X ; d - normal stress contour N(y), loads in direction Y .

Special analyses were performed for loads due destroying of neighboring building ; 2 scenarios were examined : 1 - loads on a roof of staircase due top fail ; 2 - loads on side walls of staircase due falls from side. Non - linear FEM analyses were performed for most loaded zones of walls. All numerical (FEM) analyses in this work were performed using universal software packages " LIRA" (LIRA Soft ,Ukraine) and " SCAD " (SCAD Soft, Ukraine) .

7. LIMIT (MAXIMUM) LOADS FOR JOINT CONNECTION

As it was mentioned above, reviewing structure belongs to a category of so named " mobile " structures . A regime of " repeating use " is the main special property of such type buildings. It assumed, that numerous assembling and disassembling and changes of location place are possible for these separate precast sections. It , in turn implies, that performance properties of joint connections will be saved without break during all the period of use .Usually, a guaranteed amount of assembling – disassembling cycles without need of repair is estimated according to design . It seems , that similar requests should be fulfilled by joint connections of reviewing structure . So, two levels of action intensity and limit loads were proposed for design of joint connections :

LEVEL " A " - level of actions , which permit repeating use without any repair of connections ;
LEVEL " B " - level of actions , which lead to local destruction, but not lead to total collapse of staircase structure .

It's assumed , that conditions of elastic state of material for connections should be fulfilled for actions of level " A" ; limited plastic deformations are allowed for actions of level " B " – repair of joint connections with a replace of it elements , in cases of need , are assumed here.

Limit values for vertical " **P(ult,z)** " and horizontal " **T(ult,x)** " and " **T(ult,y)** " loads per joint connection were estimated for levels of action " A " and " B " by results of following strength checking conditions :

a) shear of bolt cross-section ;
b) tension of patch plate (for a cross-section weakened by holes) ;
c) puncturing for a sloped cross - section of patch plate ;
d) bending of box type detail in out off plane direction .

It was found , that most critical conditions are : shear of bolt cross - section and puncturing ; Corresponding values of limit loads **P(ult**) are : by bolt shear – 79 t (112 t *) for LEVEL " A " , 99 t (124 t *) for LEVEL " B " ; (* - here in brackets - values in case steel Class 10.9 is used instead of steel Class 8.8) ; by pending of side plate - 72 t (101 t **) for LEVEL " A ", 95 t (l34 t) for LEVEL " B " (** here in brackets - values for deducted stress concentration factors) . This lowest value of **P(ult)** = 101 t was used to estimate maximum allowable bending moments **" M (allow) "** for reviewing structure in both main directions :

for direction " X " : **M(allow ,x)** = 720 tm , for direction " Y " **: M(allow ,y)** =1625 tm

It should be mentioned, that values of **P (ult)** and **M(allow)** were estimated for specially taken limitations for joint connection design to obtain a simple and ordinary solution : bolt diameter – 24 mm , thickness of side plates - 16 mm , type of bolts – non - preloaded . In such cases , when load - carrying capacity of joint connection will limited the field of application for reviewing structure, various design solutions for joint connection should performed (with increased number and diameter of bolts, increased number of connections , use of devices with energy absorption) .

8. FIELDS OF APPLICATIONS . CHECKING CRITERIA

As reviewing structure belongs to a category " mobile structures " , it can be placed at zones of various seismic intensity factors " Z " ,various ground conditions and have various number of stories, according to type of neighbour existing non - seismic building . So, it looks important to estimate possible fields of application for reviewing structure by loads and story number already on a stage of preliminary design . Corresponding estimations for fields of application were performed for seismic intensity factor " Z " values 0.1, 0.2 ,0.3 ; categories of ground – B, C , D, E and number of stories from 2 till 12 . Following checking criteria were taken into account for reviewing structure :

- maximum allowable bending moment for reinforced concrete box type cross – section ;
- maximum allowable shear force for reinforced concrete box type cross – section ;
- maximum allowable ground stresses ;
- overturning safety factor conditions ;
- sliding safety factor conditions ;
- strength of joint connections ;

Main conditions and results of performed checking :

a) load – carrying capacities of box type cross – sections by bending moment and shear force are enough to withstand loads of most critical conditions (Z = 0.30, ground category – E) for any number of stories. Conditions of cross -section checking : class of concrete - B40 , steel for reinforcement : f(d) = 3400 kg/cm2 ; ratio of reinforcement – 0.40 –0.80 % . Software " RCCOLUMN " (ACECOMS , Thailand , code ACI-318-05) was used for checking. Values of 11.0 kg/cm2 and 12.0 kg/cm2 were taken as allowable shear stresses for concrete B-40 and B-50 , correspondingly .

b) allowable ground normal stresses were taken as 10 ,20 and 30 t/m2 with a factor K = 1.50 due to non-uniform distribution of stresses , according to Israel Standard IS-940 . Allowable uplift ratio for shallow foundations – 1/5 . Weights of structure and shallow foundation were

taken into account . Here, taken sizes of a foundation plate - 6.40 x 9.30 x 0.60 m . In cases, conditions of checking aren't fulfilled, variants with mat foundations aren't permitted and an alternative solution with pile foundations should be selected.

c) checking for overturning and sliding safety conditions is presented on diagrams of Fig.8a and Fig.8b, correspondingly. Here, **M (over)** - acting (overturning) bending moment and **Q (slid)** - acting (sliding) shear force on a level of foundation, **M (hold)** and **Q (hold)** - holding bending moment and shear force, correspondingly. Diagrams of safety factors **K (ov)** and **K (sl)** are presented at top parts of Fig. 8a and Fig.8b. Values of allowable safety factors are 1.50 (2.00) - for overturning and 1.20 (1.50) - for sliding (according to Israeli Standards IS-940 and IS-413) are marked at upper diagrams by horizontal dish lines .

Conditions of checking are fulfilled in cases, value of holding moment **M (hold)** is located higher, than of value of acting moment **M (act)** and a safety factor **K (ov)** higher, than one was taken as allowable for overturning conditions is provided ; by analogy, value of shear force **Q(hold)** should be located higher, than value of **Q(act)** and a corresponding safety factor should **K (sl)** be provided .

In opposite cases , variants with mat foundations aren't permitted for use. An alternative solution – cap of piles should be used. A bottom ribbed plate (with ribs in a ground, like keys) should be used in cases, sliding conditions only aren't fulfilled.

d) strength of joint connections was checked and corresponding limit loads were estimated for LEVELS " A " and " B " of seismic action . It was found , that fields of application for proposed structure are limited by load- carrying capacity of joints mostly . <u>For seismic zone factor Z = 0.3 :</u> number of stories shouldn't be more , than 4 for ground categories B, C and D , and 3 - for ground category E ; <u>for seismic zone factor Z = 0. 2</u> : height of structure is limited by 5 stories for ground categories C and D , and by 6 and 4 for ground categories B and E, correspondingly ; <u>for seismic zone factor Z = 0.1</u> : number of stories is limited by 4 and 6 for ground categories E and D, correspondingly, and could reach 12 for ground categories B and C. In cases of need, another types of joint connections should be designed and used .

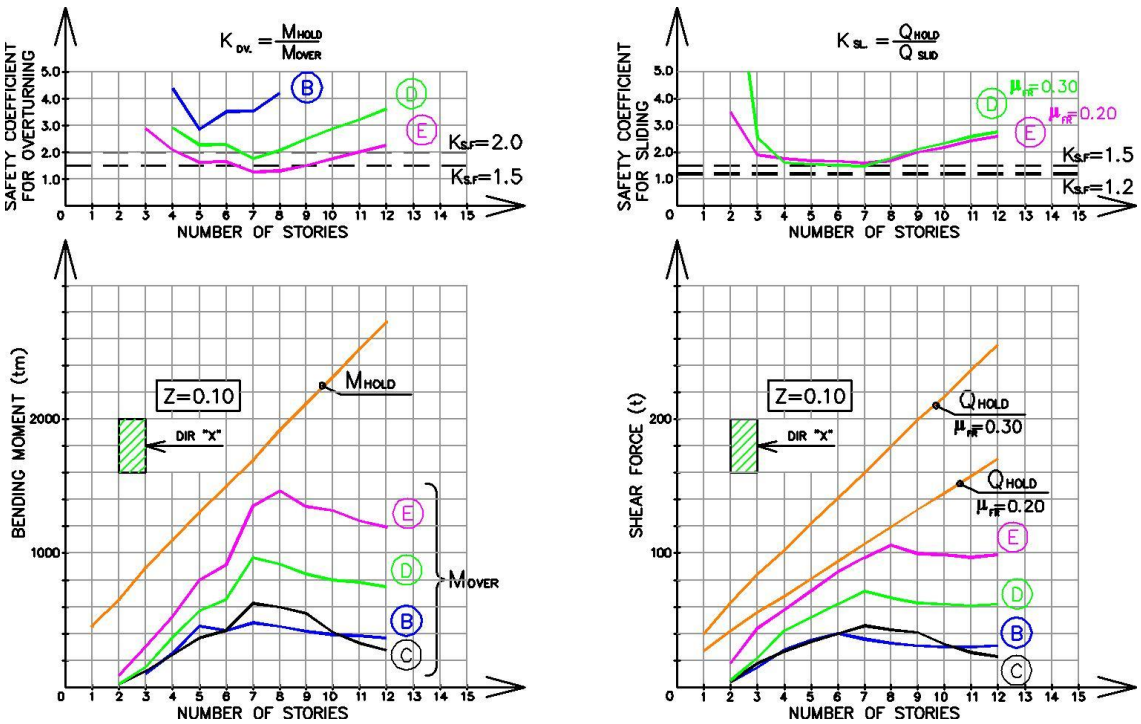

Figure 8. Fields of application by checking criteria :
a - by overturning safety factor conditions ; b - by sliding safety factor conditions

9. CONCLUDING REMARKS

An engineering solution of staircase structure for evacuation was proposed. Series of numeriacal analyses were performed to estimate limits of load - carrying capacities for the structure and it elements ; fields of application were defined for various seismic conditions and number of stories . Structural design drawings were elaborated . It's planned to perform experimental investigations of joint connections on fragments to estimate more correct values of joint rigidities . Design of additional types of joint connections for cases of extra loads is also planned .

10. ACKNOLEDGEMENTS

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