Improving the resistance of frame buildings to emergency impact through voltage regulation

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Abstract. In recent decades, especially after the September 11, 2001 attacks, more and more attention has been started to pay to the problems of the progressive collapse of frame buildings. This problem is especially topical while constructing the buildings with an increased level of responsibility. This problem is mostly solved by duplicating of supporting structure elements which results in significant increasing the cost of building structures. However, there is the other approach: by using the tension resisting ties, strained in accident, the structure can be relieved. Under this study a numerical experiment has been performed using the Scad software to proof this theory. For the numerical experiment there was chosen a building with two bays each 30 meters long at 6 meter intervals of load-bearing structures. According to the results of numerical simulation more than 20% of the supporting structures’ material has been saved compared to the absence of ties. This approach can be taken to the construction of almost all frame buildings with an increased level of responsibility and allows saving material.

1. Introduction
The American Society of Civil Engineers (ASCE 7-16 [1]) considers that progressive collapse is an extension of structural failure from section to another, and it may cause the total portion destruction or even progressive collapse of the whole structure.

There is a worldwide trend of building progressive collapse analysis in design and construction [1-5]. This trend has gained particular ground after the events of September 11, 2001.

Some years ago some ill-fated progressive collapses caused a press hype; suffice it to recall the numbers of victims, degree of damage or social impact such as Ronan Point (London, 1968) and Capitán Arenas (Barcelona, 1972), the U.S. Marine Barracks (Beirut, 1983), the Argentine Israelite Mutual Association (Buenos Aires, 1994), the A.P. Murrah Federal Building (Oklahoma, 1995), the Sampoong Department Store (Seoul, 1995), the buildings of the World Trade Center (New York, 2001), and the Achimota Melcom Shopping Centre (Acra, 2012). Due to the attention given to these and other collapses, there idea appeared that there is a need for the buildings resistant to local damages without disproportionate damages. This efficiency must be gained especially for the critical infrastructure buildings such as hospitals, power stations or for the buildings with a large number of people or open to the public, for example, schools, sports centers or commercial buildings.

The collapse of the World Trade Center in 2001 [6] caused the growing interest in progressive collapse and an increased financial support for research. Lots of experiments have been conducted. However, some questions still need additional researches. There is even a demand for resilient
buildings able to recover after the collapse, maintaining functionality which is generally defined as physical resilience at the urban infrastructure systems. Therefore, the resilience of a building is defined as the structural property of robustness and a capacity which allows to restore or even improve level of efficiency before the event.

In a building structure, the most serious local damage occurs when one or more vertical load-bearing components (e.g. columns or walls) fail, leading to a chain of failures that ends in the total collapse of the entire building or a large part of it. To avoid progressive collapses, alternative load paths must be available for the load supported by the damaged column to be transferred to neighbouring elements. If efficient alternative paths are not available, progressive collapse is inevitable unless further design measures are introduced (e.g. key element design, segmentation).

Taking cue from progressive collapse analysis’ results significantly complicates the design of frame buildings [7-11]. It should be noted that the buildings designed for seismic areas are most adapted to progressive destruction [12]. Frequently to build the construction resistant to progressive collapse requires using duplicate structures. Similar designs were proposed by Rybkin I.S. [13]. However, all these structures are characterized by increased material consumption and, as a consequence, increased cost. [14]

The author advises the other approach to solve this problem - the usage of tension regulation during upkeep of buildings. There are quite a lot of publications on tension regulation during upkeep of buildings, both domestic and foreign [15-18]. Tension regulation allows to save material by stress redistribution during upkeep of buildings by using special devices called actuators.

The object of the study is to examine the possibility of tension stresses controlling in the building structures in order to reduce materials and cost of structure. The study is based on the numerical experiment finite element method (FEM) using the SCAD 21 software.

2. Materials and methods
We made a numerical experiment using the finite element method (FEM) in the SCAD software version 21.1. The structural idealization is adapted to the use of this method.

The system is represented by the set of standard parts (rods, plates, membranes etc.) called finite elements connected to nodes.

Similar numerical experiments became widespread [19, 20].

The type of the finite element is defined by its shape, by rules determining relationship between the finite element nodes displacement and system nodes, by law of physics that determines the relationship between the internal forces and internal displacements and by the set of parameters (stiffness) included in the description of this law, etc.

The node in the displacement approach diagram is represented as vanishingly small rigid body. Node position in space after system deformation is determined by the center coordinates and angles of three axes rotation rigidly connected to the node. The node has six degrees of freedom - three translations and three rotations.

All nodes and elements of diagram are numbered. The numbers of nodes and elements should be interpreted only as names that allow us to make the necessary links.

The main system of the displacement approach is used by superimposing all relations in each node. Any nodal displacements are prohibited. The conditions for zero equality of forces in such relations are resulting equilibrium equations. The displacement of the relations is the main unknown of the displacement method.

In general, all six displacements can be presented in space node structures:
1 - translation in X-axis;
2 - translation in Y-axis;
3 - translation in Z-axis;
4 - angle of rotation about X-axis (rotation about X-axis);
5 - angle of rotation about Y-axis (rotation about Y-axis);
6 - angle of rotation about Z-axis (rotation about Z-axis).
The nodal displacement numbering (degrees of freedom) presented above is used here and elsewhere and UX, UY, UZ, RX, RY, RZ are used respectively to denote the values of the corresponding translation and rotation.

In accordance with the ideology of the finite element method, the true shape of the displacement field in the element (excluded rod type elements) is approximately represented by various simplified dependencies. The error in the determination of stresses and deformations is defined as \((h / L)^k\), where \(h\) – maximum step; \(L\) – characteristic dimension. The declining error rate of the approximate result (convergence rate) is determined by the exponent \(k\), which has different values for displacements and various components of internal forces (stresses).

In order to set design scheme data, the various coordinate systems can be used and then converted to Cartesian coordinate system. The following Cartesian coordinate systems are further used to describe design scheme:
- right-handed global coordinate system XYZ connected with design scheme;
- right-handed local coordinate systems connected with each finite element.

The design scheme is defined as a space rod frame with linear displacements of nodal points along X- and Z-axis and rotation about Y-axis.

We carried out the linear static analysis.

Possible node displacements of finite element scheme are limited by external relations prohibiting some of these displacements.

The junction points of finite element (end sections of elements) have the same displacements with nodes.

2.1 Characteristics of the used finite element types
The following types of finite elements are presented in the design scheme: rod finite elements used in accordance with the mechanics of materials laws. The description of their stress state is associated with the local coordinate system, where the X1-axis is oriented along the rod and the Y1- and Z1-axis – along principal inertia axis.

The load case combinations are set automatically in SCAD.

2.2 The sign convention for displacements
According to the sign convention for displacements, linear displacements are positive if they are oriented towards increasing corresponding coordinate and angles are positive if they correspond to the right-hand screw rule (the motion is counterclockwise looking towards the axis origin).

2.3 Forces and stresses
The calculated values of element forces and stresses are presented in the calculation results “Element forces/stresses”.

For rod type elements, forces are presented in the end sections of the elastic part (initial and final), in the center of the elastic part and in the intermediate sections along the elastic part of the rod upon user request. For plate, volumetric, axisymmetric, and shell type elements, stresses are in the center of gravity of the element and in the nodes upon user request.

2.4 The sign convention for forces (stresses)
The sign convention for forces (stresses) is set as follows.

There are some possible forces for rod elements:
- N – axial force;
- MKP - torsion moment;
- MY – bending moment along the Y1-axis;
- QZ – shear force along the Z1-axis corresponding to the moment MY;
- MZ - bending moment along the Z1-axis;
- QY - shear force along the Y1-axis corresponding to the moment MZ;
Positive force directions in rods are the following:

for the shear forces $Q_Z$ and $Q_Y$ – along the corresponding $Z_1$- and $Y_1$-axis;
for the moments $M_X$, $M_Y$, $M_Z$ – in the counterclockwise direction, looking along the corresponding axis $X_1$, $Y_1$, $Z_1$ towards the origin.

We modeled a fragment of the frame of a building measuring 60 by 24 meters. This fragment has two bays each 30 meters long and four 6-meter intervals between columns. The column height is 10 meters. The column is a square tube 350x350 mm with a wall thickness of 5.5 mm. The roof frame is trapezoidal truss without gusset plates of square tubes. Vertical bracing between columns is represented by square tubes 120x4 mm. Braces between the bottom and the top chord of the truss are square tubes.

There are following load cases: dead-weight, sandwich panel weight and snow load for III snow region.

The calculation is performed for two different situations: resting on all columns and modeling the situation when one of the columns of the middle row is destroyed. The steel elements were tested in the postprocessor of SCAD. We applied the service factor 0.8 for columns 1 in the postprocessor for truss elements. The effective length factors were set automatically.

3. Results
We present the calculation results of two options - taking into account the tie, and without it. Both calculation options include removing the middle column from the design scheme (Fig. 1-6).

Figure 1. The application scheme of load generated by ties.
Figure 2. The axial force generated by dead weight.

Figure 3. The axial force generated by snow load.

Figure 4. The axial force generated by ties.
4. Conclusions
The main conclusions of the study are:
1. Summing up the results of the numerical experiment, forces in the bottom chord of the secondary truss are reduced more than twice taking into account the ties.
2. This approach allows to make more progress in comparison with traditional design – instead of increasing sections and using additional structures, it allows to increase the reliability and structural solidity by using devices for regulating stresses, called actuators [15, 21], which switch on themselves and regulate the voltage when necessary.

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