Evaluation of building collapse risk with damage localization

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Abstract. The article offers an approach to building collapse risk evaluation with damage localization. As a rule, the risk includes the probability and value of loss. The probability of failure for separate construction is determined by known methods, but for risk-management decisions these methods are too complicated. The solutions of the problem, using the specified theoretical base, are considered: for structural damages of the constructions the simple rules of criticality degree determination are used; they are based on fuzzy logic, which ensures the efficiency of structural state assessment. The represented risk assessment method is also based on technological and social loss cost evaluation for various areas under failed constructions and different accident scenarios. The risk oriented approach can be applied in few related areas of construction, from design to insurance.

1. Introduction
Buildings collapse probability evaluation is high complexity objective, furthermore achievement the benefit of probability value is impossible without social-economical consequences of accident evaluation. To calculate risk values and further achieve the goals of risk-management process, it is necessary to determine probability and areas of collapse for each individual structure failure. This assessments can be carried out during building survey and a structural survey and required special wide experience in structural safety and residual service life evaluation.

Recently developed methods for probability of constructions failure evaluation mostly required complex calculations [1-4] and still do not taking into account some different factors witch also have a probabilistic nature. Some useful data can be collected against the expert opinion using various methodologies.

2. Preliminary remarks
In economics, the risk is well-defined and simultaneously includes possibility of an positive (negative) event [5] and some measurement of this event effect. For construction analysis and planning expediently collapse (fail, damage) negative event and price of construction is used [6]. Common risk defined as multiplication of unacceptable accident probability with consequences loss (repay, repair and etc) cost:

\[ \text{Risk} = PC \]  

where, \( P \) – probability of accident, \( C \) – consequences loss cost.

3. Localization definition rules
At first in the beginning of the survey of structures condition similar building structures are selected based on constructive solutions used in building project. These include constructions that make up the frame of the building and perform the function of perceiving loads and for plant building it will be: the basement, foundations and foundation beams, columns, column ties, wall structures, crane beams, truss and truss beams, coating.

For each of the group of similar design, a detailed condition is inspected, with the purpose to identify the most and least damaged structures in the group. Further, bearing capacity reduction analysis will be done for this constructions. The influence of each construction defects and structural damages to the building safety is the degree of compliance with standards, expressed by the level of reliability. The assignment of reliability levels is based on calculations and structures survey experience according to a formalized rule, depending on the degree of compliance with the project [7]. For typical defects and damages, rules for the assignment of reliability levels that serve as a guide for surveyor was created. The reliability level based on fuzzy-logic model [8,9], which evaluate relative magnitude of a defect or deviation in comparison with normal condition (project compliance).

In addition, to analyze the state of structures, for calculation of accident risk, probable damages associated with failure of each type of structure is estimate. For this must be done:

- detailed project analysis to determine the sequence of structures collapse for various unlikely events of construction failure situations for different locations;
- the area of possible damage from collapse determination of each separate structure with taking into account structures relationships (for example, when a column of the middle row fails, collapses at least two trusses and part of the cover, based on these trusses);
- production technology analysis for area of the building ranging, depending on possible process equipment damages;
- workshops and similar areas analysis and ranking depending on workers attendance quantity and frequency in the operations, transitional and household areas.

Project analysis, which determine the sequence of structures failure and caving reveals, based on causal relationship and represents by failure sequence diagrams.

It is necessary to consider direct and reverse caving sequences, which look like this:

1) foundation soil freezing - foundation sediment - column deviation from the vertical - loads center of application displacement from truss to column - column collapse – truss collapse – cover collapse;
2) cover collapse – truss collapse - truss load limit excess – truss stems cross-section reduction – truss steel corrosion – truss coating paint damage.

Possible damage collapse area $A_d$ can be calculated with distance added by construction falling scatter. For possible collapse of brick walls and columns made of brick the area of possible damage is calculated as follows:

\[ A_d = (w + d_1 + d_2)(h + d_2) \]  

(2)

where, $w$ – wall width, $d_1$, $d_2$ – distances respectively from the bottom and top of the wall to heights, determined by special table, $h$ – wall height [10].

For coverage, the area for middle and outside spans is calculated as follows:

\[ A_d = (w + 2d)(l + 2d) \]  

(3)

\[ A_d = (w + d)(l + 2d) \]  

(4)

where $w$, $l$ – width and length of the coverage area, $d$ – distance for the coverage area located at a height of $h$.

4. Loss calculations
Risk assessment process suggests assessment of possible damage based on equipment cost analysis and loss evaluation from production idle with the involvement of relevant economists. Relative economic loss indicator $T_i$ from technological process violation:

$$T_i = \frac{T_d}{T_s}$$  \hspace{1cm} (5)

where, $T_d$ – technological process possible damage from collapse on $A_d$ area; $T_s$ – technological process possible damage from entire building collapse on $A_s$ area.

For $T_d$ and $T_s$ calculating related with costs of building restoration, equipment, technological process adjustment and losses from line downtime.

Social loss value $P_d$ calculation depending on people attendance frequency under the collapse zone:

$$P_d = \sum n_i \cdot t_i / 24$$  \hspace{1cm} (6)

where, $n_i$ – is the number of people under the possible collapse area; $t_i$ - time of people attending under the possible collapse area during the day, in hours; $i$ - number of considered cases of people in the collapse zone, depends on working hours.

When entire building collapses, the social loss value $P_s$ is calculated by the simplified formula:

$$P_s = n \cdot t / 24$$  \hspace{1cm} (7)

where, $n$ – total number of people in building; $t$ - people attending time during the day, in hours.

The relative social loss indicator:

$$P_i = \frac{P_d}{P_s}$$  \hspace{1cm} (8)

Social loss to technological process loss ratio $c_{ps}$ is calculated by matching losses from human traumatism and damages caused to technological process by collapse of the whole building:

$$c_{ps} = \frac{P_s \cdot VSL}{T_i}$$  \hspace{1cm} (9)

where, $P_s$ – social loss probability; $VSL$ – the average Value of a Statistical Life $[8, 9]$; $T_i$ – possible loss caused by technological process letup from the collapse of the entire building.

According to calculations, recommended Value of a Statistical Life in civilized countries is about $4 to $10 million AUD, USD $[11,12]$.

Total relative economic loss:

$$L_i = T_i + P_i c_{ps}$$  \hspace{1cm} (10)

Calculation of risk of an accident is proposed on collapse areas localization. Analysis of accidents in industrial plant allows set the unit of the local building collapse area - a span part within the temperature block. Then the risk of an accident is represented by the sum:

$$R_i = R_{loc,1} + R_{loc,2} + \ldots + R_{loc,i}$$  \hspace{1cm} (11)

where $R_{loc,1}, R_{loc,2}, R_{loc,i}$ – risks of local collision of each separate accident scenario.

When risks calculating, groups of similar structures are divided into two types, depending on possible consequences: structures that capable of cause a progressive collapse of part of the building or the whole building and structures that are incapable of cause a progressive collapse of part of the building or the entire building.

The risk of local collapse in a separate scenario for structures incapable of causing progressive collapse:

$$R_{loc,i} = L_i \cdot n_i^2 \cdot \left( n_i^f \cdot n_i^p \cdot \nu_{ui} \right)$$  \hspace{1cm} (12)
where $L_i$ – relative economic loss from local collapse; $n_i$ – the number of structures that falls in the considered local collapse area with the same consequences; $n_s^T$ and $n_s^P$ – are the total number of structures in the areas with the same categories of technological process loss and social loss in the area under local collapse; $v_{ni}$ – average reliability index for a structures group which failure can provide this collapse; $i$ – number of collapse scenario.

The risk of local caving in a separate scenario for structures that can cause progressive (avalanche) collapse is:

$$ R_{loc,i} = \frac{L_i}{\prod_{i=1}^{n} P_{n,j}} $$

where, $L_i$ – relative possible loss from the collapse of structure; $P_{ni}$ – average reliability index for one of structures group, $i$ – number of collapse scenario; $n$ – number of structures group for the collapse scenario.

5. Approbation

Risk of an accident at the workshop «Height 239» of PJSC Chelyabinsk Pipe-Rolling Plant (figure 1) was calculated.

![Figure 1. Span of the "Height 239" workshop of PJSC Chelyabinsk Pipe-Rolling Plant.](image)

Calculations considered the collapse of four construction types in each temperature block of the building: outside row column, middle (inner) row column, truss, outdoor sandwich panel. Workshop consists of eight temperature blocks.

The results of calculating structures collapse risk in two temperature blocks are given in the table.

| Block № | Type of construction failure | $T_i$ | $P_f$ | $P_d$ | $T_d$ | $c_{pc,i}$ | $L_i$ | $R_{loc,i}$ |
|---------|-----------------------------|-------|-------|-------|-------|-----------|-------|-------------|
| 1       | Middle column               | 0,025 | 0,0094| 3     | 525,1 | 0,229     | 0,0271| 0,0283      |
|         | Outside column              | 0,0119| 0,0068| 2     | 249,24| 0,321     | 0,0141| 0,0147      |
|         | Wall panel                  | 0,00045| 0,0448| 1     | 9,41  | 4,25      | 0,191 | 6,52·10^{-7}|
|         | Truss                       | 0,0224| 0,0105| 5     | 470,01| 0,426     | 0,0268| 0,028       |
| 2       | Middle column               | 0,0229| 0,0131| 5     | 477,31| 0,419     | 0,0284| 0,0296      |
|         | Outside column              | 0,0115| 0,0086| 3     | 241,17| 0,322     | 0,0144| 0,015       |
|         | Wall panel                  | 0,00045| 0,0448| 1     | 9,41  | 4,25      | 0,191 | 6,52·10^{-7}|
|         | Truss                       | 0,0203| 0,0131| 4     | 426,46| 0,375     | 0,0252| 0,0263      |
After summarizing the structures failure risks in each temperature block, the overall risk of an entire building accident was obtained, it was 2.42. This means that structural safety level of this workshop is sufficient, so as the actual risk is in range of acceptable values.

There are two standard risk values for overall risk [13,14]:
- normal (for new buildings) – \( R_n = 2 \);
- maximum permissible – \( R_{pm} = 19 \).

Based on the results of performed calculations, schemes for the periodicity of maintenance and structural repair of the workshop was composed, which allowed risk-oriented approach implementation to the operation and maintenance of the workshop realization.

6. Conclusion

Risk values determination model for industrial building with taking into account collapse area localization, material and social losses is developed.

Based on the research carried out in risk evaluation in the context of collapse localization the following conclusion can be drawn.

Risk value definition can subsequent provide insurance rate determination [15,16], can be used for risk-management [17,18], determination of Residual Service Live and service planning [19]. Risk value definition can be used on buildings design phase to provide more effective project cost optimization.

In future risk models can be added to BIM technology [20], which significantly simplifies the actual problems of risk-management and risk-oriented design in construction industry.

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