801. A new method for building risk level estimation under dynamic load

J. Vaičiūnas, V. Doroševas
Kaunas University of Technology, Faculty of Civil Engineering and Architecture
Studentų 48-49, 51367 Kaunas, Lithuania
E-mail: *juozas.vaiciunas@ktu.lt*, *viktoras.dorosevas@ktu.lt*

(Received 4 April 2012; accepted 14 May 2012)

Abstract. A building, as mechanical system, is composed of elements with different properties and distinctions. Vibration or shock impact action is one of the most effective methods to produce substantial qualitative and quantitative changes in such system. Buildings may be conditionally divided into three main categories: residential, public or social and manufacturing or industrial buildings. Any building during interaction with the dynamic load could pose hazard to human safety in the crowded place, particularly in the case of accidental progressive collapse. This phenomenon is a relatively rare event but study of its behavior is very important both for newly erected and existing buildings in order to reduce the number of casualties in accidents. In general, civil engineering structures such as buildings are composed of elements with different properties. Interaction between these elements subjected to shock loading can be analyzed using „missing column" or „missing slab (beam)" scenarios. It is obvious that the most dangerous buildings are those with massive gathering of people, i.e. leisure, entertainment, shopping centers, high-volume administrative or industrial buildings, residential buildings, buildings of national significance, etc. Our goal is to propose a method to assess each building on a comprehensive hazard risk level under the influence of special effects, especially when the building experiences impact loading. The result would be a given expression of building index which is called a point of risk level *D*. The use of this point summon up additional assumptions for the assessment of building as integral building system, the consequences of accidents, as well as their prevention.

Keywords: dynamic load, point of risks level, progressive collapse, prevention.

Introduction

In general, buildings can be classified according to the different criteria or attributes. However, the main classification of the buildings is splitting into three groups, namely: residential, public or social and manufacturing or industrial. Their classification is regulated as in the example [1]. According to the dominant design elements, the buildings can be conditionally divided into the beams, plates and mixed structures. Building classification is shown in Fig. 1. In spite of design of the building structure, it is constantly exposed to various types of loads. For examination of the impact model and effects it is necessary to express the influencing factors by more than one variable, for example, by the load size and its direction. As defined in [2, 3] under the effects of changes during the time, the intensity is divided as follows:

- a permanent, continuously operating (marked with "*G*");
- variable or temporary operating structure (retaining a separate item) a temporary (indicated by the letter *Q*);
- special or accidental (marked with the letter *A*).

According to [4] it is determined that to the designation of effect generally is used the letter *F*, respectively, of a characteristic and the calculated values – F_k and F_d Thus, a generalized effect is a function of *G*, *Q* and *A*:

$$F = f\left(G, Q, A\right). \tag{1}$$

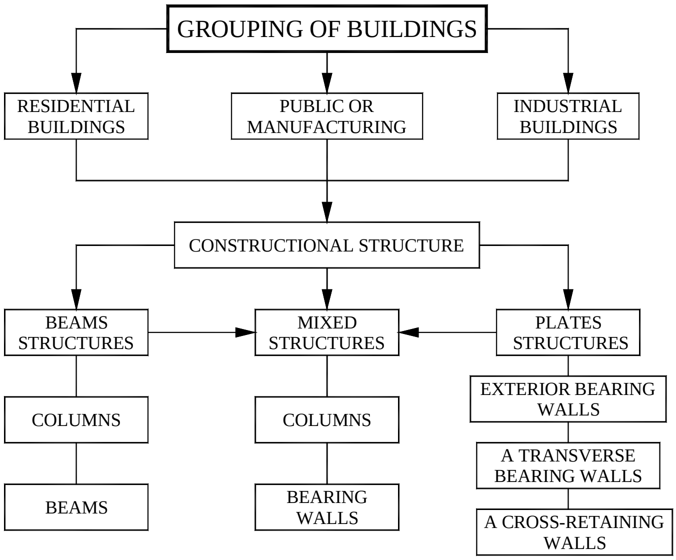


Fig. 1. Classifications of buildings

As practice shows, the most difficult is to assess the extraordinary effects that occur and impact the structure (design) with low probability and have short duration. These effects can be:

- random shocks and effects of collisions;
- effects of explosions;
- ground base subside;
- tornado like whirlwind (when a structure is in the country where their effect is unlikely);
- earthquakes (although, in the case could be considered as non-effects);
- fire effects;
- effects that may occur in extreme conditions of intense material erosion.

Although these effects occur rarely their evaluation is necessary because of specific effects triggered by the exclusive use on the structural conditions, such as fire, explosion, local blow or disintegration.

Therefore, considering the influence of these effects is the construction of safety limit state. These states description identifies the groups:

- the failure of structures - STR class;
- ground failure or excessive deformation - GEO class;
- loss of static equilibrium - EQU class;
- the failure due to fatigue - FAT class.

Experience shows that building or structure collapse depends on the errors made during facility design, construction and operational phase. For example, statistical errors caused by all three phases are distributed as given in Fig. 2 [5]. It should be noted that 41 % is attributed to the design phase (calculation errors), 15 % - incorrect loading and impact assessment, 28 % - wrong choice of design structure, 16 % - some technical issues, as well as misalignment of the individual parts of the project.

Construction phase: 77 % - insufficient quality of materials, manufacturing and assembly errors; 16 % - deviations from the project, 3 % - incorrect organization of operation, 4 % - incorrect storage and transportation.

Life phase: 30 % - corrosion, 27 % - shock, vibration, 12 % - overload, 6 % - the climate influence, 6 % - undermining, breaking; 19 % - unexplored material properties.

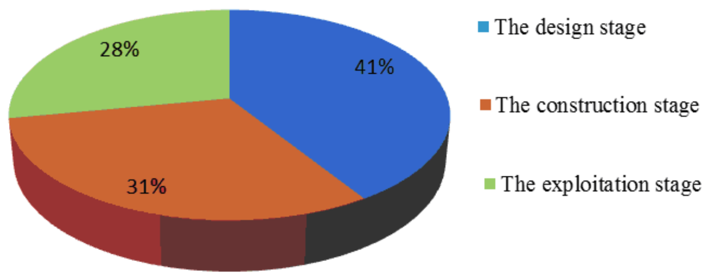


Fig. 2. The diagram of error distribution

Similarly, emerging case studies made more recently provide the following results (percentage of causes for the expression): 10 % - design standards imperfection; 36 % - inappropriate design solutions, 2 % - low quality of materials used, 38 % - low production and installation of quality, 12 % - operating deficiencies; 2 % - adverse factors coincidence. It could be noticed that the reasons of the structure collapse can vary and be dangerous for humans. For these reasons the analysis of a structure and the special effects of the interaction among the collapse causes must be performed systematically, i.e. taking into account both direct and indirect factors. The former are considered as interaction of special factors with the building or construction. Significance of this effect may be normalized to a certain value, ensuring that the static conditions are stable and there is no assumption of progressive collapse. However in the view of foregoing considerations above it is obvious that the comparison only of the direct impact with the normalized value is not sufficient. It is also necessary to evaluate all indirect factors that are different in each situation.

Problem formulation

Suppose we have a structure or design which may be subjected by dynamic effects such as the detonation of a powerful explosive. Obviously, the explosion damage will depend on the cartridge capacity, the blast site in the considered space system and the physical-mechanical characteristics of building components. As we could notice in this context it is possible to distinguish the following three main groups of characteristics:

1) the features that characterize the dynamic effects;
2) features which characterize a structure or construction;
3) properties which characterize the contact of structural and dynamic effects.

In turn, the first group of properties can be grouped under the dynamic effects of the form, such as explosive charges: spherical, cylindrical, etc. The second group of properties can be divided into subgroups according to the nature of deformation when the object is elastic body or elasto-plastic body. The third group is appropriate to distinguish in two subgroups according to the nature of contact: when the dynamic effect and object contact is direct or indirect, for example, when another medium is involved (e.g. air or water).

On the other hand, keep in the mind that under the dynamic influence of the load on the structure of the building, progressive collapse is possible due to descend of influence of destroyed elements and increase in loading of adjacent elements by exceeding limit.

Due to this main reason, collapse of building structural systems sometime occurs. It is obvious that the issue of process analysis and study of building components with dynamic interaction effects, taking into considerations presented assumptions, is intricate, and can be decisive in the formulation of two main tasks:

1) creating a mathematical model, which would examine responses of building structural system to dynamic effects;

2) development of evaluation criteria and methodology of consequences.

The first task of the decision may deal with only a differentiated physical and mathematical modeling. Mathematical modeling, based on analytical and numerical methods, allows an extensive investigation interaction of exerted dynamic effects with the structural elements, but it also has some limitations. The latter are concerned with the evaluation of boundary conditions. The structure determines limitary conditions. Therefore, in order to evaluate all its features, such as the individual elements of the stiffness and so on, it is appropriate to use the application elements, extreme elements, finite differences and finite element method as well as numerical procedures of larger quantities to compensate the advantages which can provide analytical methods. It is important from these positions to apply finite difference and finite element methods by using the corresponding CAE software such as ANSYS. Upon disposal one of the previously described mathematical modeling gets information about the building as a mechanical system response to dynamical impact. This information can be expressed through the dynamical action due to displacements of structural elements distribution function.

Thus parameters are obtained as a direct response of dynamical impact on the considered structure system, which characterize state of the system elements and create preconditions for prediction of the consequences. This raises a problem of assessment of the simulation results and deriving the consequences.

Method of evaluation

Let's try to imagine any of the building structural systems which are subjected to the dynamic load or an extraordinary impact. Structural system response to the dynamic effects can occur in different ways and it will depend on the dynamic impact of direct or indirect influence.

Obvious example is the terror attack on US on 11 September 2011. Exposed by any dynamic load of building structure, which will assume the direct impacts of energy, part of it can be transferred to the related construction or their elements. This transfer of energy to other elements can cause progressive collapse, if the safety limits of elements state conditions would be exceeded.

On the other hand, the indirect impact, such as increased temperature or design faults in the building construction system, parameters of safety limit state could be reduced and that indirectly influence the possibility of progressive collapse. Thus, complex criteria are required in order to evaluate and predict the response of building structural systems to dynamic loading.

The search of this response creates new conditions for new type of evaluation of such events by method using a point of risk level [6]. The most important is the establishment of a tested building structural system or its individual objects, exposed to dynamic loads and the level of consequences, which is determined by a complex index, called a point of risk level *D*. Level of risk can be assessed not only by direct impact of the dynamic object, such as explosive strength, but also by indirect impact, possible secondary processes after explosion and process design faults influence in the structural constructions system. Thus, the point of risk level is a complex response of a structural system to dynamic loads and it is evaluation characteristics, which allows not only improve the safety but also to group and evaluate the potential chance of progressive collapse and the consequences of the accident.

In general case the point of risk level *D* can be expressed through structural system interaction with the extraordinary impact by the displacement, which is obtained by mathematical dynamic modeling:

$$D = \lg\left(\frac{s_d}{s_t}\right)^{\alpha_c}, \qquad (2)$$

where: s_d - maximum displacement of the contact zone due to dynamic impact; s_t - very small displacement approved by certain physical and mechanical characteristics of materials; α_c - index that expresses the indirect influence of factors, as a function $\alpha_c = f\left(\alpha_i\right)$.

It should be noted that considering the response of the structural systems to dynamic impact should be related standardized displacements and pressures with the building safety limit state also with the generalized minimal impact from equation (1) i.e., calculated by running only permanent action *G*. Thus, the approved parameters value will depend only on the magnitude of the dominant structural character of the building and permanent action.

The variables of the indirect action function on the indicator are the possible indirect factors, such as inflammability of building structural elements, being of hazardous and harmful substances or technologies and so on, coefficients of structure affecting factors. This function can be calculated as follows:

$$\alpha_c = 1 + \sum_{i=1}^{n} \alpha_i \ . \tag{3}$$

Consequently, if the present system does not contain indirect action factors, then $\alpha_c = 1$. In this case according to equation (2) the point of risk level expresses only a direct action on the dynamic impact and in the physical sense, for example, it is linked to the Richter magnitude [7]. The level scales in all other cases are $\alpha_c > 1$.

The accomplished analysis has identified the following key factors of indirect action and their impact on the express criteria:
1) criteria k_1 - quality of structural elements and its state;
2) criteria k_2 - duration of building exploitation and life time;
3) criteria k_3 - influence of fire;
4) criteria k_4 - vibration and its effect;
5) criteria k_5 - action of harmful substances and their influence;
6) criteria k_6 - quality of the mutual connection of the structural elements and the influencing factors;
7) criteria k_7 - operating conditions and their influence;
8) criteria k_8 - state of building engineering systems and their influence;
9) criteria k_9 - interaction of structure and ground, its influence.

In this context, let us rewrite equation (3) as follows:

$$\alpha_c = 1 + \sum_{i=1}^{9} k_i = 1 + k_1 + k_2 + k_3 + k_4 + k_5 + k_6 + k_7 + k_8 + k_9 \ . \tag{4}$$

If there is no action of the indirect action criteria (k_i), then $\alpha_c = 1$ and a point of risk level of building may be similar as the Richter magnitude. If the structural construction system is subjected to all aforementioned indirect action criteria (k_i), then $\alpha_c > 1$ and a point of risk level of building may be determined by equation (2).

The most importance criteria is k_1, because insufficient quality of materials, manufacturing and assembly errors in construction phase constitute 77 % of all errors. For this case, we suggest methodology to determinate and calculate the criteria of quality of structural elements and its state. In order to illustrate the method of evaluation k_1, compare displacements of RC slab from the same impactor with initial velocity interaction (Fig. 3). The following two states of RC slab were used in the analysis: (A) - normal RC slab state – concrete and metal materials condition are good; (B) - RC slab have metal material defects, for example, wantage of the reinforcement beams.

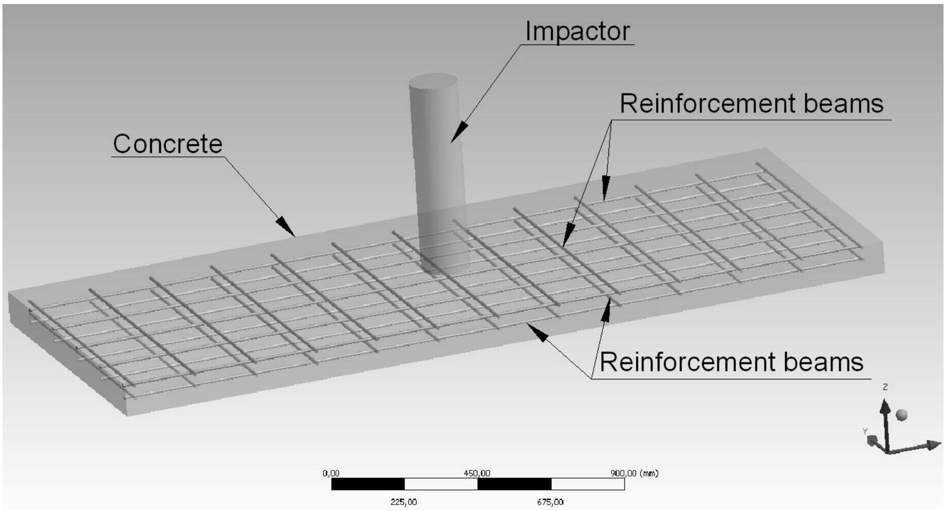
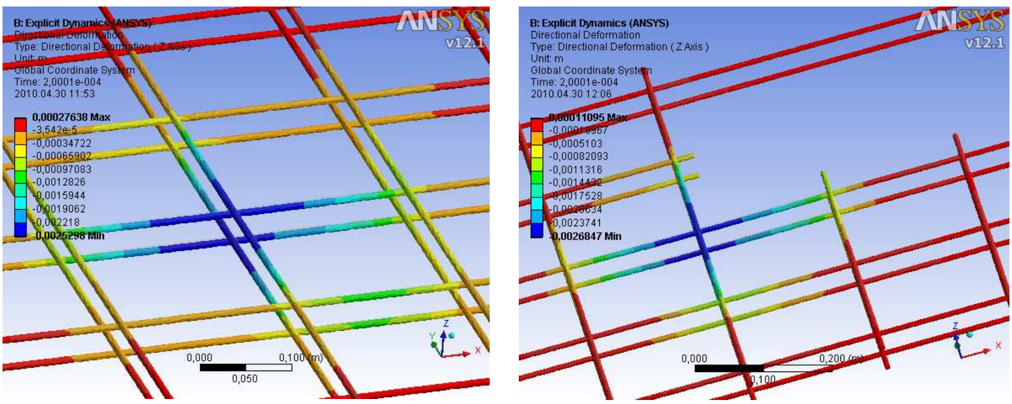


Fig. 3. Model of RC slab interaction with impactor

The problem simulated numerically is sketched in Fig. 4 and numerical investigation from same impactor with initial velocity of up to 9 m/s interaction of two state**s** of RC slab (A, B) was carried out with FEA modeling by using the Explicit Dynamics analysis in ANSYS [8,9]. The impactor was modeled as rigid 197 kg weight of cylindrical body with the density of 7830 kg/m^3, with an elastic modulus of 159 GPa and Poisson's ratio of 0.2.



a) State A b) State B

Fig. 4. Fragments of RC slab interaction with an impactor

After realization procedure of mathematical modeling we obtain information about the response of RC framed structure to the impact, for example, maximum displacements s_A and s_B appearing under shock impact loading in state A and B at time instant t. Different displacement of RC slabs is characteristics of the state A and B. If maximum displacement appearing under shock impact load in state A corresponding to the good quality of structural constructions elements and its state, i.e. criteria $k_1 = k_{1A} = 0$, then in state B, by taking into account that $s_B > s_A$, criteria k_1 will be:

$$k_{1B} = \frac{s_B - s_A}{s_A}. \tag{5}$$

For example, maximum displacements s_A and s_B appearing under shock impact load in state A and B at time t, value of criteria k_1 is given in Table 1.

Table 1. Values of calculation of the criteria k_1

t (ms)	s_A (mm)	s_B (mm)	k_{1A}	k_{1B}
0.1	1.0847	1.0999	0	0.014
0.15	1.8132	1.8766	0	0.035
0.2	2.5298	2.6847	0	0.061

Criteria k_2 – k_9 are under development but in order to illustrate the whole method of evaluation to analyze the problem. The dynamic load is single stick of dynamite with approximate magnitude value 1.2 on the Richter scale. We have the same structural system of buildings with different values of quality condition given in Table 2.

Table 2. Values of calculation of the point of risk level of building

The subject of research	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9	α_c	D
Building 1 (ideal)	0	0	0	0	0	0	0	0	0	1	1.2
Building 2	0.09	0.08	0.04	0.02	0.02	0.03	0.02	0.03	0.02	1.35	1.28
Building 3	0.12	0.08	0.05	0.01	0.04	0.03	0.02	0.03	0.02	1.4	1.29
Building 4	0.23	0.1	0.06	0.04	0.05	0.03	0.02	0.04	0.03	1.6	1.34
Building 5	0.46	0.12	0.07	0.07	0.08	0.03	0.02	0.05	0.04	1.94	1.42

The problem simulated numerically is sketched in Fig. 5.

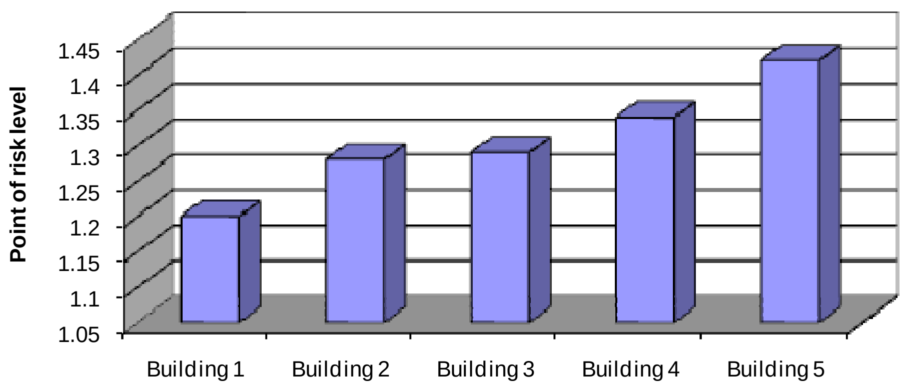


Fig. 5. The diagram of building estimation

Hereby, presented method enables to evaluate structures subjected to dynamic loading, for example, exerted by the earthquake or explosion. On the other hand, it is clear that it is necessary to solve the task of evaluating the criteria of structure for calculating the point of risk level.

Conclusions

The paper demonstrated that the evaluation of structures subjected to dynamic loading is sophisticated because the level of risk depends not only on direct impact, such as explosive strength, but also on indirect impact, possible secondary processes after dynamic loading. The proposed methodology can be used for developments in vibroengineering of dynamical systems. Some conclusions are important in civil engineering:

1. The proposed method can be used for evaluation of the interaction of structures with dynamic impact and estimation of the point of risk level for a civil structure.
2. The main causes of structural collapse under dynamic loading are associated with errors subdivided into three categories: facility design related errors, errors made during construction phase, and operational errors.
3. Application of the proposed method creates additional presumptions to estimate consequences of progressive collapse and may help to predict those consequences.

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