Computer-aided design of civil building structural connections constructed in earthquake-prone regions

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Abstract. More than 300000 earthquakes occur worldwide every year. The main goal of the earthquake-resistant design of buildings and structures in earthquake-dangerous regions is to assure the safety of people and the security of material assets. Significant damage or even complete collapse of buildings are not uncommon because of the inadequate strength of their structural framing elements and connections. The modern approach in the theory of seismic design is in the avoidance of using brittle materials in construction, as well as in regarding as acceptable a local damage that does not lead to the collapse of the entire structure. Often when designing a reinforced concrete building, an engineer is mainly concerned with a strength of a structure, while not paying enough attention to its ductility and ability to absorb the energy. Construction of buildings and their connections based on the structural composite steel fiber concrete in earthquake-dangerous regions is very promising due to the superior ability of this material to resist to static and dynamic loading, which could be controlled by an engineer.

1. Introduction

Major earthquakes lead to mass casualties and damage. Like the other natural disasters, such catastrophic events are almost impossible to predict. Today the protection of structures from seismic hazards is a problem of the great importance [1].

The modern theory of the seismic performance postulates the acceptability of local damage, which do not lead to the destruction of the entire structure of a building. Another important statement of the theory is that the use of any brittle material for the construction should be avoided. Track record of the recent earthquakes shows that despite the significant advances in the earthquake engineering, the problem is far from its complete solution.

2. Earthquake protection measures

Earthquake-proof engineering experts consider the active earthquake protection at the soil-foundation interface to be a real source of improvement of seismic performance of a structure [2, 3]. This method relies on the building's ability to displace in the horizontal direction.

The disadvantage of such systems is the significant local stress arising in the reinforced concrete (RC) structures under vertical loading, which requires additional reinforcement to bear it. Utilizing the construction composite material steel fiber concrete (SFRC) allows one to increase the load bearing capacity and reliability of the structure, to avoid the excessive reinforcement, and to simplify the construction technology.

Among the most vulnerable elements of structure experiencing repeated loads are the beam-column and column-column nodes and joints.

The load tests of the beam-column joints in reinforced concrete frames show that the main requirement necessary for the normal operation of a joint, especially when it is subjected to repetitive reversing loads, is the restriction of lateral displacements of concrete. If such a requirement is not met, then concrete would break under the bending moment, which is much less than the moment calculated without taking this factor into account. Few load cycles are enough to reduce the load bearing capacity of the joint almost to zero. Moreover, even relatively small stress leads to the formation of large slant cracks [4, 5]. In order to increase their strength and endurance, the joints are reinforced with horizontal welded wire mesh or stirrups with vertical bars [5, 6].

3. Reinforced concrete frame structures

RC frame buildings have been widely constructed in earthquake-dangerous regions around the world [5, 6]. They feature flexibility, long-periodic natural oscillations, significant plastic reserve, readily accessible framing material. Track record of the recent earthquakes shows that RC frame or braced frame structures possess high resistant to the intensive seismic impact. The most vulnerable elements of the structure are joints and structural connections.

The peculiarity of the earthquake-proof structure design and construction is in a great number of factors to be taken into account, which affect the operational reliability and stability of a building under the seismic action.

Column-to-column connections of the frame structure should be made rigid, as they are intended to bear the bending moment caused by the horizontal load under the seismic action. The joint design includes the steel shoe at the end of each column and has two versions: with or without strengthening plates. The recommended design of the connection with strengthening plates incorporates reinforcement bars with a cross section area which is 25% more than that of reinforcement bars in the mating columns (Figure 1 (*a*)). A connection without strengthening plates is used when the joint is compressed axially (Figure 1 (*b*)).

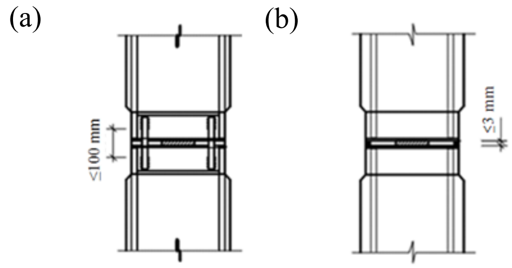

Figure 1. Column-column connection with steel shoes: (a) with circular strengthening plates; (b) without plates.

Parts of beams and columns adjacent to the rigid frame nodes must be reinforced laterally with closed stirrups placed according to the calculations, but not less than one stirrup per 100 mm (Figure 2). Flaw in the frame nodes and adjacent zones leads to the structural damage or even to the collapse of a building.

The most important element affecting the structure behavior under seismic action is a beam-column joint. The beam-column joint with a hidden steel corbel is common in the civil frame structure buildings, as it is more aesthetically attractive in the interior space design than the open corbel joint. Connection of the beam to the column is made by welding the protruding reinforcement rods and further grouting (Figure 3). The joint has corrugated mating surfaces intended to form concrete keys, and closely spaced transverse reinforcement bars both in the beams and the column.

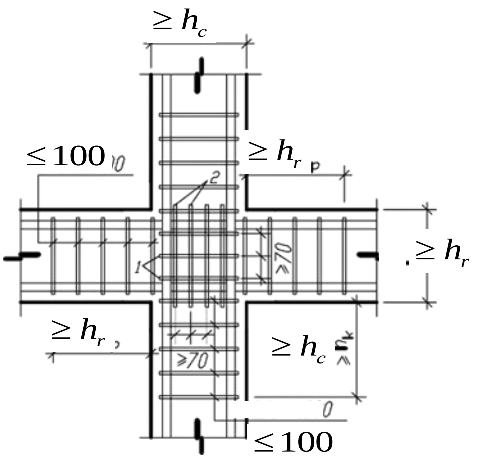

Figure 2. Transversal reinforcement of the central part of a beam-column joint and parts of beams and column adjacent to the joint: 1 — additional stirrups; 2 — additional vertical bars around the perimeter of stirrups.

A high reinforcement ratio in beam-column joints of the RC frame structure enables the utilization of steel elements in the joint design. Thus, one can employ the plastic deformation capacity of steel. However, the use of such a solution is limited by economic concerns and the need in corrosion protection.

Existing RC elements of passive earthquake protection cannot fully resist the seismic action because of the brittleness of concrete. The use of ductile materials with high deformability is required, one of them is the modern structural composite already mentioned above, i.e., steel fiber concrete.

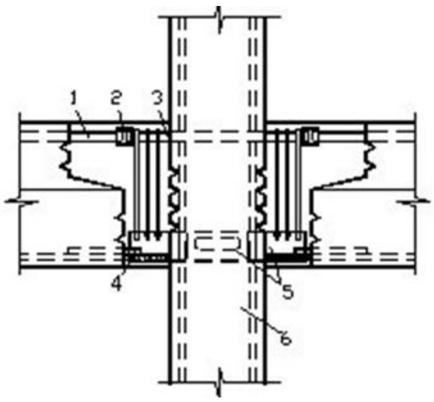

Figure 3. The joint with hidden steel corbels: 1 — beam reinforcement; 2 — welding; 3 — column reinforcement; 4 — strengthened reinforcement; 5 — angle steel corbel with hole for grouting; 6 — column.

4. Structural composite steel fiber concrete

SFC outperforms initial concrete in deformability due to its high plasticity and fracture toughness [7]. Furthermore, SFC features the higher fretting resistance, fatigue resistance, and impact resistance, and has the ability to undergo significant deformations without destruction. It maintains the high strength even after the beginning of cracks formation and has the high tensile and shear strength.

The test results show that using SFC one can ensure the effective protection of the structure elements from brittle failure [7, 8, 9]. The properties of SFC depend on the properties of concrete used in its production, its strength and deformation performance, as well as on the geometric parameters of steel fibers (diameter d_f and length l_f), their stress-related properties (tensile strength R_{sf}, elastic modulus E_{sf}, etc.), their adhesion to concrete matrix, and the volumetric content of steel fibers in concrete [7-12].

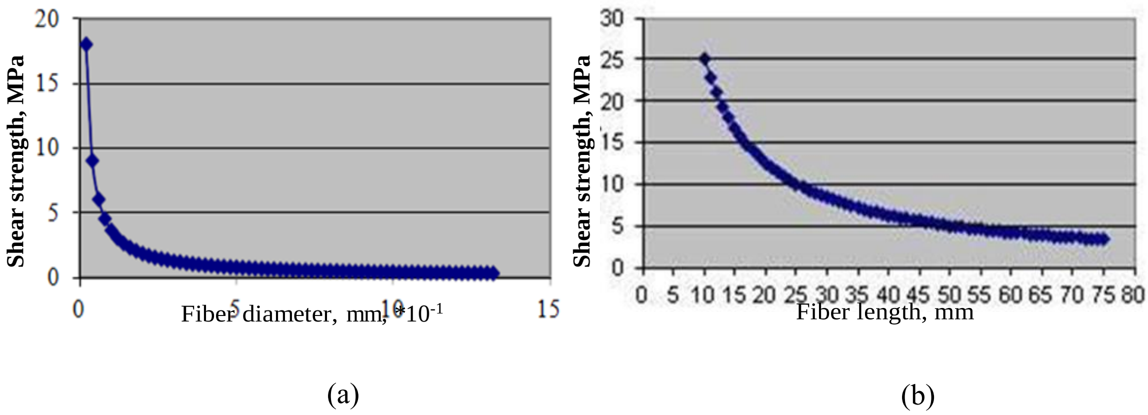

Figure 4. Dependence of SFC shear strength under dynamic load on: *(a) diameter and (b) fiber length.*

A large number of parameters affecting the mechanical and physical characteristics of SFC gives the way to control its properties and create the material suitable for each structure element depending on its stress and strain state, that allow one to improve the existing solutions of the frame structures earthquake protection, and also to develop the new ones, including the active earthquake protection.

Numerical simulations and experimental studies of strength and deformation properties of SFC under dynamic load show that in order to use SFC efficiently for structure connection nodes in the earthquake-dangerous regions one should use steel fibers of small diameter and length (Figure 4).

5. Determination of the SFRC grouting zone in a rigid beam-column joint

Using SFC instead of confinement reinforcement in joints and connections provides their plastic deformability due to mechanical and physical properties of SFC and simplifies their design, as the reinforcement construction and concrete casting are combined into one process in this case [7,8,10].

The results of experiments performed in Kiev Institute of Civil Engineering (VUGASU) shows that the replacement of wire mesh reinforcement of a structural connection with SFC grouting reduces the tensile deformation by the factor of 2–4, and the node deformations increment is 1.5–2 times less than in the standard design [8].

In order to solve the problem under consideration, the software complex has been developed, comprising of the standard software packages SCAD, AutoCAD, Paradox database, and the custom numerical calculation module “Earthquake protection”. The application software has been carried out using the Delphi design environment and the Object Pascal programming language.

The zone of a joint, where SFC should be used, is determined according to the stress fields obtained by the calculation of static and seismic loads in a framed structure adopting the SCAD application. Based on this calculation, the frame structural design is generated, as well as a file with stress values in all structural elements. After static and dynamic simulations based on the stress values obtained, the design calculation of the building earthquake protection elements is performed, and their load bearing capacity and rigidity are checked. The most unfavorable combinations of stress values in the corresponding finite elements are written to the file, which serves as an input for the custom design calculation application “Earthquake protection”.

The source data for the static and seismic load calculation are the construction area, soil conditions, the building importance class, the structural design of a building or calculated stress values in structural connections, the connection type according to the material used (RC or SFC). The user provides all necessary information, such as the building area description, design and spatial arrangement of the building, using the GUI dialogs and controls.

The goals of simulation of the support frame of a building are to ensure its load bearing capacity under combined action of static and dynamic loads, and to limit the building oscillations within the range which is safe for people and the building structures. For this reason, following the generation of the structural design, static and dynamic calculations have been performed with various stress combinations.

When the user selects a structural node number, the software analyzes the corresponding file and compiles the list of all elements of the structure adjacent to the selected node. As the stress values are known at least either at the end of the element and/or in its middle cross section, one can determine the stress in any point of the element using the quadratic approximation. The cross section, where the internal moment is greater than or equal to the external one, would be the boundary of SFC grouting in the joint (Figure 5).

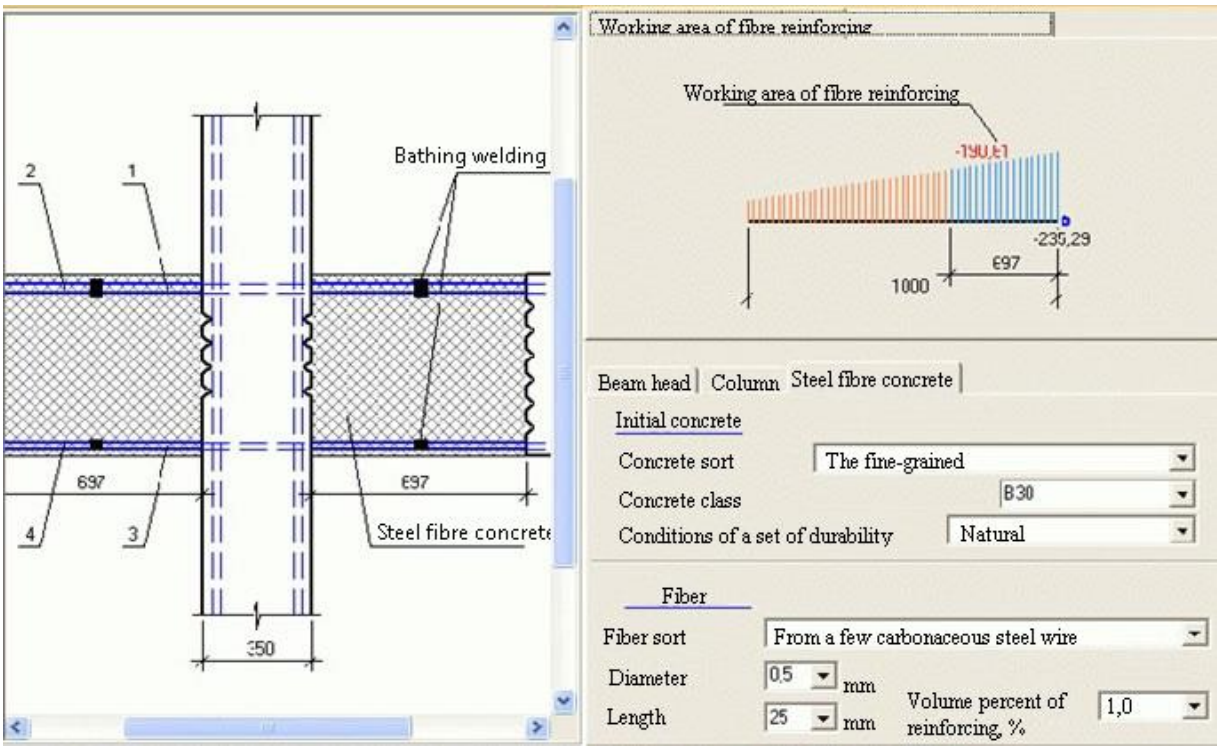

Figure 5. "Earthquake protection" module GUI. Determination of SFRC grouting zone of beam-column joint with compound reinforcement: 1, 3 — joint working reinforcement ∅25 A400; 2, 4 — beam protruding reinforcement ∅25 A400.

The present solution ensures the structural node plastic deformability due to the SFC ability to ductile fracture and energy absorption, as well as its ability to accommodate significant deformations without any damage and high shear resistance. Thus, load bearing structural elements and their joints could be designed to meet the prescribed performance characteristics, which are determined in accordance with possible external actions (i.e. static and seismic loads) [10-12].

6. Conclusion

The results of studies of the SFRC utilization in structural elements and their connections allow one to increase the serviceability and the expected life of civil buildings constructed in earthquake-dangerous areas without increasing their cost and any additional manpower effort. Use of the computer-aided engineering tools enables one to design structures, which meet the prescribed performance characteristics appropriate for the intended operational environment. This approach opens the way to achieve technical and economic performance of civil building projects superior to their existing counterparts.

Acknowledgement
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