DISINTEGRATED STRUCTURAL SCHEME FOR SEISMIC DESIGN OF CORES IN RC CORE-FRAME BUILDINGS

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Abstract
Two methods for seismic design of cores in reinforced concrete core-frame buildings are considered. The first method is intended for buildings violating the height limits assigned by current seismic codes, whereas the second one is intended for buildings complying with these limits. Some weak points in these methods are pointed out and an alternative approach to design a group of cores in core-frame buildings is presented. It is concluded that the first method is unreliable whereas the proposed approach, which is a modification of the second method, makes it possible to prevent a total collapse of the core-frame building after its partial failure in a strong earthquake. A numerical example illustrating this approach is given.

Keywords: reinforced concrete, seismic design, cores, columns, walls, permitted height limits, model of reinforced concrete behavior, size effect, ill-posed problems.

1. Introduction
In regions of considerable seismic risk, the ASCE code [1] and the Russian seismic code [2] set height limits of the order of 50 m for reinforced concrete core-frame buildings (in absence of seismic isolation). At the same time, construction of much higher buildings of this type is permitted in certain seismic regions, for example in the region of Los Angeles, California [3]. This disagreement is reflected in diversity of methods for seismic design.

On one side, according to a method developed by the TBI (Tall Buildings Initiative) working group, which is presented in the Guidelines [4] and referred below as the TBI method, the established height limits are obsolete and systems comprising two or more cores should be avoided as adding to complexity of analysis and uncertainty. On the other side, a method included in the Guidelines [5] and referred below as the parallel walls' assembly method, is intended for buildings that comply with the established height limits and comprise two or more reinforced concrete cores.

The aim of the present study is to consider this issue. The weak points of the above mentioned methods are pointed out. An alternative approach to design of buildings with a group of cores is presented, illustrated by a numerical example and discussed. It is assumed in the frame of the present study that the seismic forces, acting on the building, are known, for example adopted in accordance with one of seismic codes. The scope of the paper is restricted to regular in elevation buildings.

2. Comments on current methods
<u>TBI Method</u>

Models of reinforced concrete behavior, which are adopted in this method for nonlinear response time history analysis of walls and cores, employ the stress-strain relations of concrete and steel as material characteristics of the reinforced concrete behavior and, therefore, relate to "smeared crack" models (e.g. [6]). As known [6, 7], analysis of reinforced concrete structures by finite element methods yields non-objective (depending on the size of finite elements) results in the post-peak range of behavior. From a formal viewpoint (e.g. [8]) it means that corresponding boundary value problems of structural analysis are ill-posed and, in order to obtain correct solutions, appropriate regularization procedures should be developed. From an engineering viewpoint (e.g. [9, 10]) it means that "smeared crack" models employ incomplete sets of material characteristics and should be appropriately modified in order to capture size effects in the pre- and post-peak ranges of the reinforced concrete behavior and localization of deformation (formation of discrete cracks unsuitable for "smearing").

Models of concrete behavior with extended sets of material characteristics are an object of continuing research, e.g. [11, 12]. Meantime, results of nonlinear analyses of reinforced concrete structures, including analyses based on "smeared crack" models, should be considered "with a healthy degree of caution and skepticism" since "… we still do not understand well, let alone have accurate models for, all aspects of reinforced concrete behavior" [7].

The TBI method is intended for design of structural systems with lateral seismic force resistance concentrated in the central reinforced concrete core. Due to a lack of a reserve lateral load path in these systems, the use in their design of insufficiently accurate (in particular, ignoring the size effects) models of the reinforced concrete behavior, like the models adopted in the TBI method, can be a reason of their failure in a strong earthquake.

Parallel Walls' Assembly Method

According to this method, seismic forces in any direction are distributed between the cores' walls of the same direction in proportion to their rigidities. Ignoring the contribution of the cores' walls of transverse direction raises the seismic reliability of the building and provides it with a high degree of redundancy but in an irregular way, depending, in particular, on the seismic force direction and cores' geometry. Besides, in case of asymmetric arrangement of cores in the building, the method yields distribution of seismic forces between the cores' walls that violates the equilibrium equations.

3. Proposed approach

Early failure of ground floor columns during an earthquake is assumed in order to "compensate" for inaccuracies in modeling the reinforced concrete behavior and for other seismic design uncertainties. In case of the ground floor columns' failure, the floor diaphragms of the building should be considered as relatively flexible plates (membranes) rather than plane discs. Transformation of the floor diaphragms to membranes provides additional degrees of freedom to the cores and, as known from the theory of thin-walled beams [13], may be accompanied by significant growth of stresses in the cores. In order to prevent the cores' failure, each core is designed as a separate unit according to the following algorithm.

1. Divide the area of the building into parts adjacent (tributary) to the cores and calculate for each part its area and the coordinates of the gravity center.
2. Distribute the lateral seismic forces acting on the building between the cores proportionally to their tributary areas.

3. Calculate the bending moments, the normal and shear forces at transverse sections of the cores due to the partial seismic forces applied at gravity centers of the respective areas. Calculations are performed for lateral seismic forces acting in a direction specified by angle φ.
4. Calculate the longitudinal steel ratios ρ(φ) at transverse sections of the cores' walls.
5. Return to steps 3, 4 with varying values of φ ($0^\circ \le \varphi < 360^\circ$) and calculate ρ = max ρ(φ) for cores' walls and walls' edge elements at each floor of the building.

In a current version of the program KIR [14], which implements the above algorithm, the linear elastic model of concrete behavior is adopted, cores are assumed to be of open section, in analysis of the cores by the finite element method each core is considered as an assembly of planar walls (panels in the biaxial stress state) and walls' edge elements (rods in the uniaxial stress state), φ = 0˚, 45˚, 90˚,…, 315˚, values of ρ(φ) are calculated using the algorithm described in [15], simplified for the case of uniaxial bending.

4. Numerical example

Given: a ten-story building 10 x 3 = 30 m by height and 11.69 × 17 m in plan (see Fig. 1), subjected to lateral seismic forces, that are distributed in accordance with the equivalent lateral force procedure, the seismic response coefficient C_s = 0.049, a gravity load of intensity 8kN/m^2 is uniformly distributed at all floors and on the roof, the concrete strength f_{cd} = 17 MPa and the longitudinal steel yield strength

f_{yd}=348 MPa. The building is provided with 2 cores containing 2 safe rooms [16] at each floor and a core containing a staircase.

Part of the results obtained using the program KIR is presented in Figs. 2.

5. Discussion

The proposed approach is similar to the method adopted in the ASCE code [1] for seismic design of reinforced concrete dual systems with special shear walls and special moment frames. To ensure structural integrity both of them provide components of the structure – the cores and a frame, respectively, - with additional (redundant) capacities. These additional capacities are unnecessary from the viewpoint of conventional analysis, which is based on the (irrelevant for reinforced concrete structures in the cracking stage) assumption of compatibility of deformations in the whole structure.

The proposed approach is a modification of the parallel walls' assembly method, since in both of them disintegrated structural schemes are adopted and cores are considered as assemblies of planar walls in the plane stress state. Unlike the parallel walls' assembly method, the proposed approach makes it possible to take into account the torsional strengths of the cores' walls and the presence of coupling beams near the cores' edges.

6. Conclusions

1. The TBI method is unreliable since it employs models of the reinforced concrete behavior that are incapable to capture size effects and localization of deformation, and structural analyses, based on these models, may yield non-objective results.
2. The proposed approach enables to prevent a total collapse of the building after its partial failure in a strong earthquake.

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Figure captions

Fig. 1. Building plan (dimensions in cm, columns not shown).

Fig. 2. Disintegrated structural scheme, tributary areas (sq. m.) of cores C1, C2, C3 and longitudinal steel ratios/areas (sq. cm.) in core C3 at ground floor level.

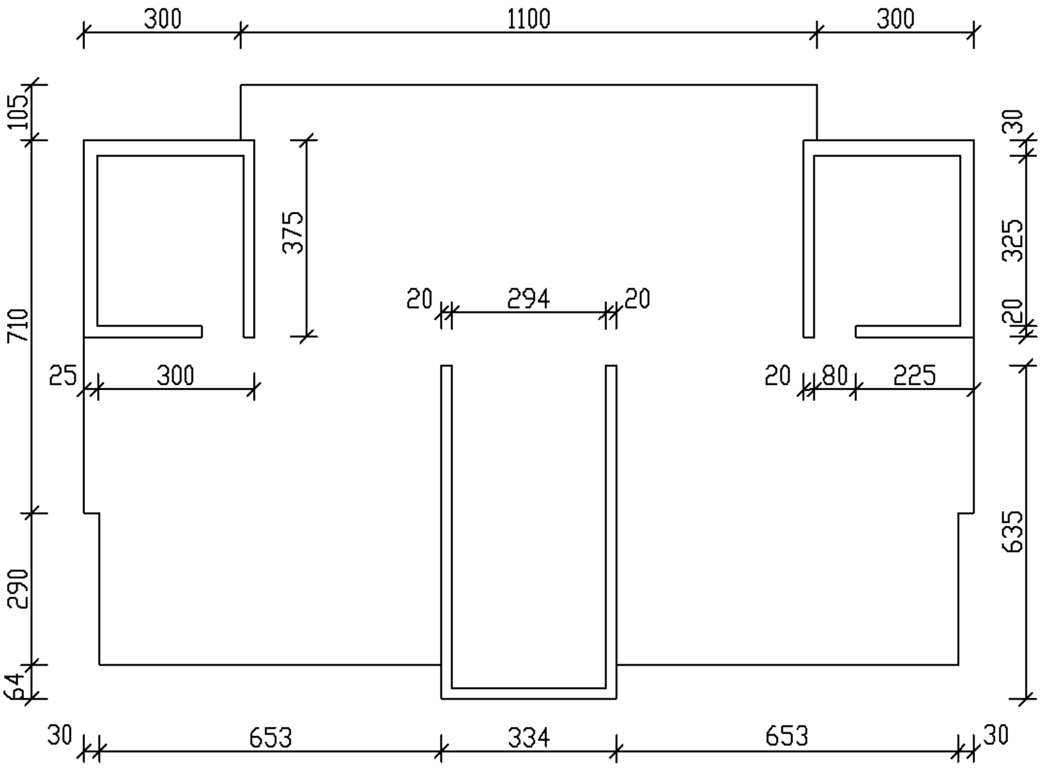

Fig.1.

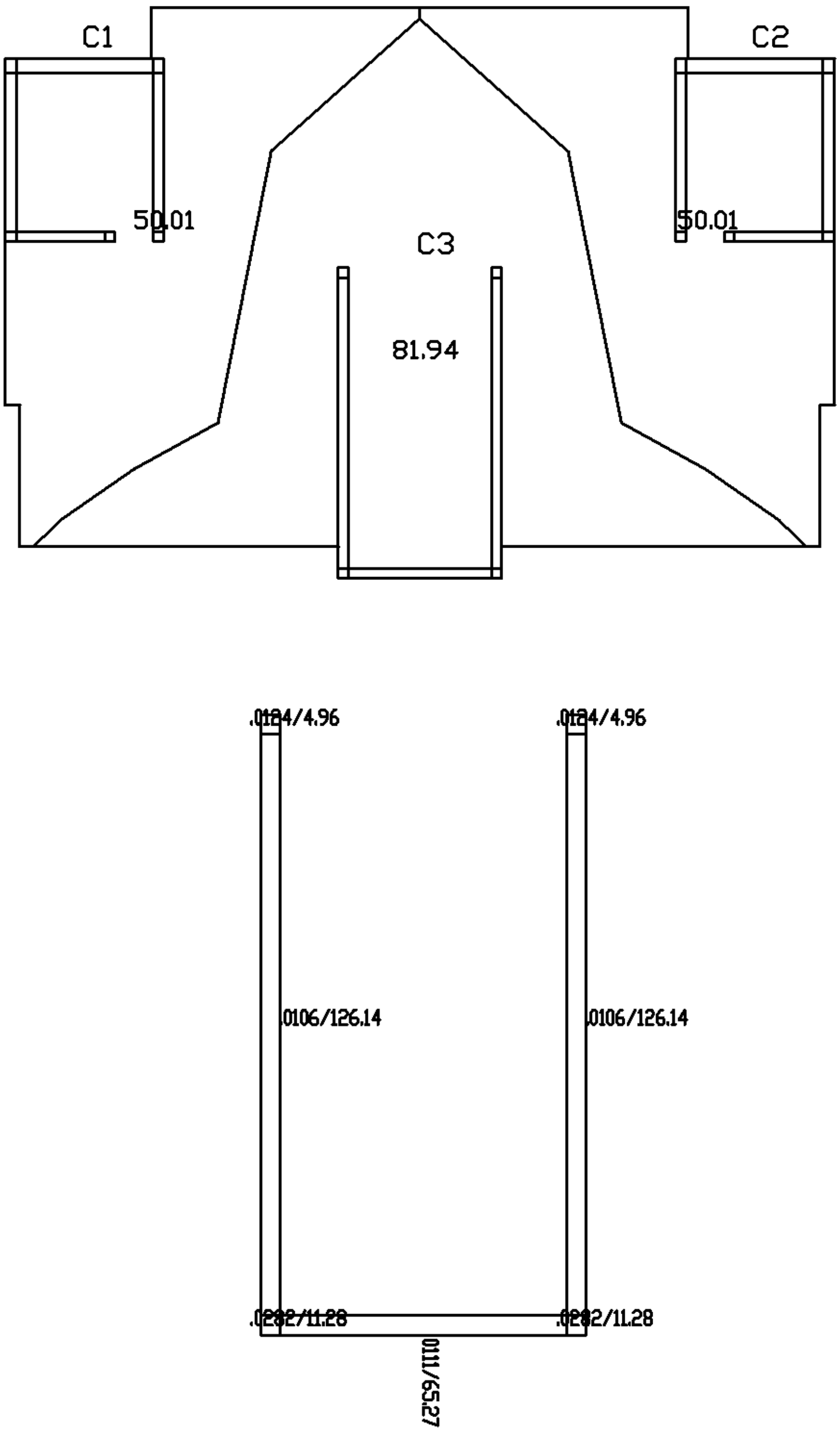
C1
C2
C3
50.01
50.01
81.94
.0124/4.96
.0124/4.96
.0106/126.14
.0106/126.14
.0282/11.28
.0282/11.28
0111/65.27

Fig. 2