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RECENT TRENDS FOR EVALUATING TORSIONAL EFFECTS IN REINFORCED CONCRETE FRAME BUILDINGS

BY

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Abstract. The present paper deals with the actual trends concerning the study of the the inelastic torsion behavior of reinforced concrete (RC) asymmetric buildings using a 3D two storey building subjected to pure torsion. The crack patterns, the maximum crack widths at service load level, torsional strength, torsional ductility, and post-cracking reserve strength results of the experiments are discussed. The main parameters include the volumetric ratio of torsional reinforcements, the compressive strength of the concrete, and the aspects concerning the ratio of the cross section. Some preliminary conclusions regarding the adequacy of the post-cracking reserve strength for specimens with relatively low amounts of torsional reinforcement and its relationship to the ratio of the transverse to the longitudinal reinforcement factors in addition to the total amounts of torsional reinforcement are highlighted.

Key words: torsion; reinforced concrete; inelastic behaviour.

1. Introduction

In the case of multistory buildings based on a reinforced concrete frame structure, the cross sections can be simultaneously subjected to normal (*i.e.* axial force and bending moment) and tangential (*i.e.* shear and torsion) forces. As we know the actions of these forces at the section level are nor separately either individually, thus it necessary to combine their influences in order to achieve a more realistic approach. The method of combining these effects has been a vast research field for scientists.

For the analysis of models one can differentiate two distinct approaches. In the first one, the model is generally described as fully coupled, being the most accurate and complex of the available sectional model approaches [1]. This kind of models requires meshing, and for complex models, for the computational efficiency, some condensation of the formulation in order to reach optimum efficiency could be necessary. The computational cost is however high, due to the iterative procedure required for the concrete state determination, as material, under a 3D stress state, formulation based on the hypo elastic models [2]. Furthermore, the concrete strength under a 3D stress state is calculated based on a sophisticated 5-parameters plasticity model, developed by W i l a m and W a r n k e [3].

A secondary approach was developed by including the torsion within a one dimensional (1D) frame element, based on membrane models, such as the modified compression field theory (MCFT) of V e c c h i o and C o l l i n s [4], the softened truss models (STM) of H s u and M o [5] and P a n g and H s u [6] or any derivation of them [7], [8]. For these models, considering some experimental observations, the reinforced concrete section subjected to torsion is treated as a hollow section, with either a constant or a variable wall thickness, depending on the forces acting on the section. The walls are then discretized into wall-element systems, that satisfy the governing equations defined by means of the equilibrium and compatibility of the behavioral model [9], [10]. A diagonal compression field theory (CFT) was used by L e u n g and S c h n o b r i c h [11] to study the post-cracking behavior of reinforced concrete sections.

C o c c h i and C a p p e l l o [12] used the concept of the discrete truss model to analyse reinforced concrete sections subjected to axial force, bending moment and torsion. Further extension of the formulation in the truss model as well as a computer implementation for the case of bi-axial bending was made later by C o c c h i and V o l p i [13]. R a h a l and C o l l i n s [14] employed the MCFT model to study the shear and torsion interaction as well as a full interaction between normal and tangential forces within a reinforced concrete and presstressed section. Moreover, some of the models in the second category are based on a combination of fully coupled models and membrane models based on the MCFT material model [15]. In all these models, the section is divided into three distinctive regions based on the state of stress (*i.e.* 1D, 2D and 3D), and for each region an appropriate and consistent behavioral model is adopted to reduce the computational cost associated with the material state determination [15]. Nonlinear frame elements that include torsional degrees of freedom (DOFs), are so far not so well developed, except some results coming from very few researches [16],…,[18] about . Further, existing sectional models which takes torsion into account, have not been implemented within 1D frame elements so far, and their performance in multi-story 3D frame structures has not been studied [19].

2. Structural Analysis

When performing the inelastic analysis of spatial reinforced concrete frames under static loads the diagonal compression field theory is used. This analysis is performed according to a peculiar discrete truss model of the beam element behavior having any mechanic, geometric and reinforcing characteristics, in the presence of axial, bending and torsional interaction.

In some of the studied numerical analysis, developed with a suitable software, it was shown that the theoretical results are good in comparison with the experimental results and the interaction effects on the cracking and ultimate behavior of the structure have a big influence. The local stress or strain distribution over the sectional fiber or concrete spalling could be of great importance at sectional level of structures but the studies interest is in the global response of the element and recording the load distribution and ultimate loading capacity of the system with good accuracy. The accuracy and efficiency of the new element for recording the global behavior of the reinforced concrete frames is verified by numerical examples. Test results on reinforced concrete members under pure torsion show three distinctive stages before failure: un-cracked, cracked *vs.* without yielding of the reinforcing bars and, finally, cracked with the yielding of the reinforcing steel. A schematic representation of the sectional torque *vs.* twist curve is given in Fig. 1 updated form V a l i p o u r's and F o s t e r's study.

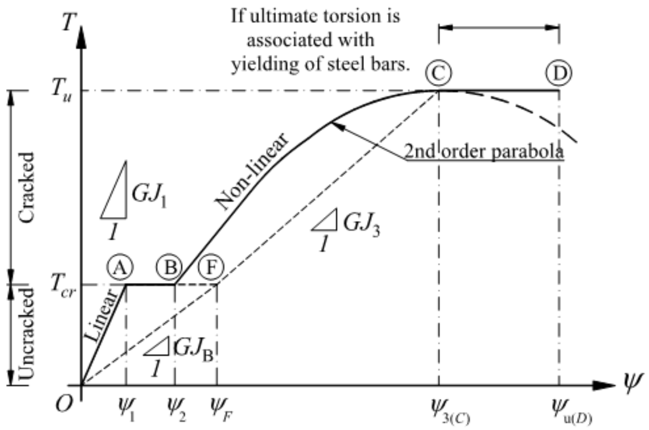

Fig. 1 – Outline of the torque *vs.* twist curve for a section under pure torsion.

Two distinct stages can be defined in the cracking process of an element: the pre-cracking stage and the post-cracking stage. In the pre-cracking stage we can define the cracking torsion, T_{cr}, through the following relation:

$$T_{\text{cr}} = \left[1 + (n-1)\rho\right]\left(\frac{A_c}{u_c}\right) f_{\text{cr}}, \tag{1}$$

where: A_c is the gross area of concrete, u_c – the perimeter of the concrete cross-section and f_{cr} – the cracking strength of concrete which is taken as equal to the direct tensile strength of the concrete. The factor $[1 + (n – 1)]\rho$ on the right side of eq. (1) takes account of the reinforcing steel on the cracking load, where ρ – the total volumetric ratio of the reinforcement and n – the modular ratio ($n = E_s/E_c$, where E_s and E_c are the elastic modulus of steel and concrete, respectively).

After the cracking limit is reached the longitudinal and transverse steel controls the stiffness; the torsion is resisted by a truss action of compressive stresses in diagonal concrete struts and tensile stresses in longitudinal and transverse reinforcement with no shear transferred along the crack surface of the element. A more elaborated study shows that the frame solid elements are replaced by hollow sections of effective thickness, t_e , and the longitudinal reinforcements are assumed to be distributed over the section's perimeter evenly [21].

3. In Depth Analysis

By studying the pattern of the cracks, their width, the post-cracking reserve strength and the torsional ductility for frame elements with less torsional reinforcement under pure torsion we can create a more realistic scenario of the behavior of these elements undergoing the previously mentioned actions. For the analysis have to be considered the following parameters: volumetric ratio of transverse to longitudinal reinforcement, f_c (compressive strength of concrete), cross-sectional characteristics of the structures solid and hollow regions and the minimum requirements for these elements of torsional reinforcement proposed in other researches and tests.

If we develop a more realistic approach on the subject of crack appearance and patterning we can have more control on this phenomenon. In this case, the quantity of reinforcement in the characteristic transverse cross-section has to be high enough to ensure the distribution of the cracks along a controlled surface and that the reinforcement does not yield at the first cracking. According to the theory of elasticity, when the specimens are subjected to pure torsion, the first inclined crack normally initiates in the middle of the wider face of the cross section.

The tests carried out for specimens having similar amounts of torsional reinforcement, the torsional cracking strength is lower for those with hollow sections or greater aspect ratios, [21]. As a result, the reinforcement started to resist external loads at an earlier load stage for such specimens (s. Fig. 2 [21]).

Recent studies on the static torsional provisions of Eurocode 8 [22] show that the static torsional provisions generally are satisfactory and have a restrictive propriety when the considered structure has a large torsional stiffness. On the other hand, when considering flexible torsional models this provision is on the downside. It is also the case of buildings designed in high class of ductility, which require a more complex analysis.

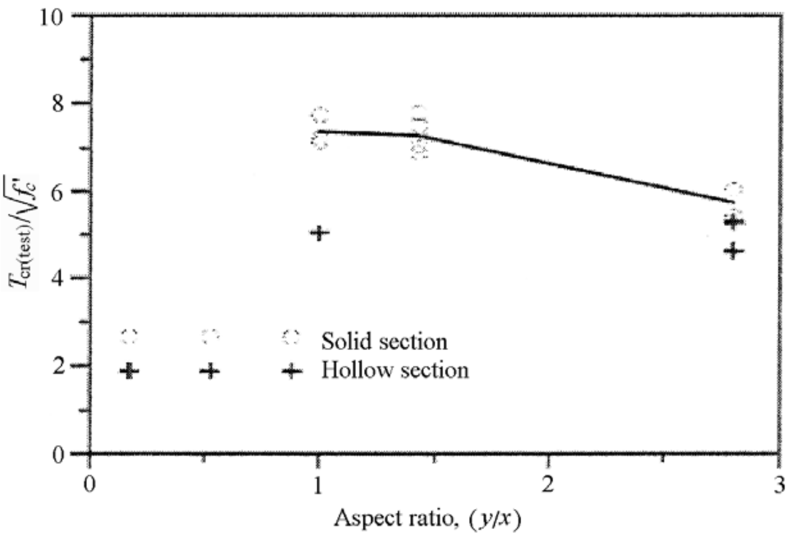

Fig. 2 – Normalized cracking torsional strength *vs.* aspect ratio relationships for the test specimens.

4. Conclusions

The particular issue of torsional effects on reinforced concrete structure represents a result of increasing the variety of constructions with different classes of architectural demands, leading to a complexity of dynamic models needed to be analysed and filtered through the latest requirements of design codes [22]. Although the needs of numerical studies to evaluate the torsional response of structures, the present state of the art exposed in this paper shows that actually this important issue has been presented in the latest decade by very few researchers. Most of the extended studies carried out by Valipour, Foster, Chiu, Fang, Young, Shiau have been focused however only on simple structures. The corresponding numerical results needed to be validated by considering new parameters as: plane shape variation, ratio of torsional reinforcement as well as the distance between mass and stiffness center at each floor level. By evaluating the effects of elastic behaviour on structural system subjected to pure torsion especially for dynamic analysis it is revealed that the amplification of the displacement in elastic analysis can be used only as a rough estimation of torsional behavior since in elastic range the dynamic system are becoming conservative.

Further studies need to be conducted for the evaluation of torsion influence. When conducting in order to understand the full potential of structural members and the fulfillment of feasible design criteria as recommended by European codes it should be also investigated whether the local effects such as strain–stress distribution over the section and the concrete spalling could be of importance for further evaluation studies.

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TENDINȚE RECENTE PENTRU EVALUAREA EFECTELOR TORSIONALE ÎN STRUCTURILE PE CADRE DIN BETON ARMAT

(Rezumat)

Din analiza şi sinteza studiilor recente privind evaluarea efectelor din torsiune la structuri şi elemente din beton s-au identificat aspecte importante ce pot influența comportarea structurală, respectiv: distribuția fisurilor pe sistemul structural din cadre de beton armat; lățimea maximă a fisurilor, precum şi influențele variației acestora asupra comportării ansamblului structural. Se prezintă şi unele aspecte legate de evaluarea rezistenței la torsiune a elementelor structurale din beton armat precum şi a capacității de rezistență la torsiune, ca urmare a rezervei suplimentare de capacitate din zona plastică a armăturii structurilor din beton armat solicitate la torsiune peste limita de elasticitate. Parametrii principali în evaluarea torsiunii în structuri în cadre din beton armat sunt următorii: raportul volumetric al armăturii de torsiune, rezistența la compresiune a betonului, precum şi raportul laturilor secțiunii transversale în cauză. În final sunt identificate concluzii prelimitare privind influența asupra comportării la torsiune a structurilor din beton armat a raportului dintre cantitatea de armătură longitudinală şi cea transversală, correlate cu rezistența elementelor din cadru după pragul de curgere al armăturii.