Transactions of the **13th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

Unintended out-of-plane actions in size effect tests of structural concrete

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ABSTRACT: The paper is part of a larger research program into the causes of size-effects in structural concrete that involve international cooperation among the Universidad Nacional de Tucumán (UNT), Argentina, the Imperial College of London (ICL), G. Britain, and the National Technical University of Athens (NTUA), Greece.

The results obtained through the application of a nonlinear finite element analysis using material models having extensive tested reliability, pointed out a possible connection between unintended out-of-plane actions and the ultimate strength of reinforced concrete (RC) structures. The computational analysis brought up unacceptable discrepancies only in those cases where possible unintended out-of-plane actions could not be negligible nor neutralized. Herein, it arises the need of experimental research on such situations to inquire into the role played for those actions and, if they really were detected, to try to link them to some suitable parameters that would allow to take into account their presence in numerical analysis.

1 INTRODUCTION

It should be noted that most of the research work on size effects carried out to date has been confined to cases where structural concrete is subjected to plane-stress conditions. Such conditions can easily be imposed in analysis but, in real structures, it is difficult, if no impossible, to prevent the occurrence of out-of-plane actions. Admittedly, in a controlled experiment such actions can be minimized and, when comparing analytical predictions with experimental values, it is implicitly *assumed* that out-of-plane actions are small enough to have negligible effects on the experimental established structural behavior.

It has recently been argued, however, that ignoring small stresses often leads to misinterpretations with regard to the causes of the observed structural behavior of concrete, since the presence of such stresses usually has significant effect on concrete (material) strength (Kotsovos 1982). It would appear, therefore, that, before any attempt is made to modify current material models so as to allow for size effects, it is essential to clarify the effect of the small unintended of out-of-plane actions --inherent in any experiment-- on structural concrete behavior.

To this end, the possible connection between size effects and the development of unintended of out-of-plane actions are aimed at investigating in the present work. If such a connection really exists, then, in situations where the unintended of out-of-plane actions are self-evidently negligible (such as, for example, the case of slabs subjected to uniformly distributed or concentric point/path loading), the predicted behavior should be essentially independent of size effects. Similar predictions should also be obtained in situations where the presence of reinforcement is sufficient to withstand the additional small stresses caused by unintended eccentricity of the applied load (such as, for instance, the case of RC beams, with stirrups, subjected to the (intended) in-plane transverse loading). The lack of stirrups in the latter case may be expected to lead to size-effect dependent predictions of structural concrete behavior.

The present work is intended to verify the possible validity of the above postulates. It has its origin in the use of a finite element analysis (FEA) package (described at length at Bédard et al. 1985-1986; González Vidosa et al. 1991a-b) that has been found to yield realistic predictions of the behavior of a wide range of structural concrete configurations. The package was used to predict the behavior of RC slabs and beams, with and without stirrups, for which there is ample experimental information describing structural characteristics. The obtained results (Ramallo et al. 1993) appear to verify the validity of the postulates, i.e., it was shown that, while the predicted behavior for the slabs and the beams with stirrups were essentially independent of any size effects, such "size effects" were evident in the predicted response of the beams without stirrups. The experimental investigation of the causes of size effects in the latter case forms the subject of an international cooperative program of research involving the structural laboratories of the Universidad Nacional de Tucumán (UNT), Argentina, the Imperial College of London (ICL), G. Britain, and the National Technical University of Athens (NTUA), Greece.

2 EXPERIMENTAL PROGRAM

Eight rectangular reinforced concrete beams without stirrups were subjected to (intended) in-plane point loading. The specimens were divided into two series: *Series 1* and *2*. Both two series consisted of completely similar beams having the same degree of reinforcement but differing in size (Figure 1). They were reinforced with straight continuous ribbed steel bars and had no shear reinforcement but outside the test length (outside the bearings) to ensure that failure will occur within the test length. Also, steel plates (identical to those used at loading and bearing points) were welded at the end of the longitudinal steel bars to prevent them for debonding. The loading was applied at two symmetrically situated points so positioned that $M/Qh = a/h = 3$. The geometric dimensions were in the ratios: $D1{:}D2{:}D3{:}D4 = 1{:}2{:}3{:}4$. The longitudinal reinforcement in each beam consisted of a suitable combination of two or three bars of ribbed steel (type III - 42/50) with diameters of 6, 12, 16 and 20 mm., providing a degree of reinforcement (reinforcement percentage) of $\rho \sim 1.65\%$ in all cases. The steel plates (affixed with epoxy resins) under the loads and over the roller bearings were varied in size to conform to dimensional similarity. Two beams of each size were made and tested. All the beams of a series were manufactured with the same concrete composition at the same time. However, due to the laboratory facilities, three batches of concrete mix were necessary to cast all the forms thus adding some scatter onto the concrete strength.

The beams and cylinders were cured into their molds under damp cloths and were removed from them after 5 days, and then stored at about 20°C and 65% relative humidity waiting for being tested. The cylinders were tested at different ages (7 days, 28 days and at the date of beams testing). The beams were loaded with 2 symmetrically arranged concentrated loads; the specimens belonging to *series 1* were submitted from 6 to 9 incremental load stages with, in all cases, intermediate load maintenance while crack mapping was carried out. On the other hand, *series 2* was loaded uninterruptedly until failure as the crack patterns were correctly registered in *series 1* and in order to preserve the specimens for any accidental movement.

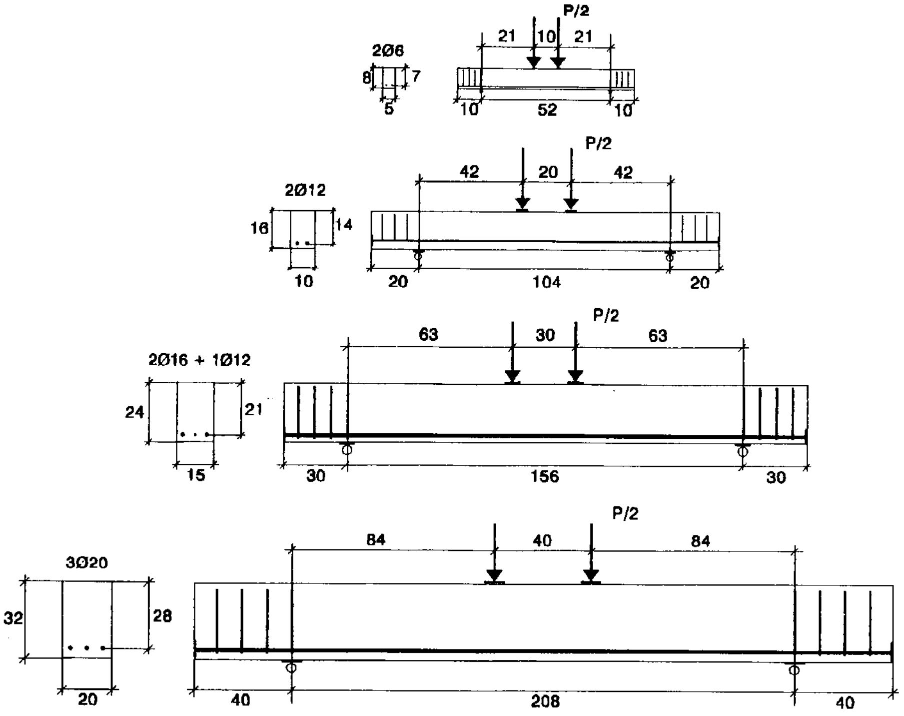


Figure 1. Dimensions of the test beams.

During all test of each specimen, deflections (horizontal and vertical ones) were automatically measured through a computational managed central for data acquisition. Also, the applied load and concrete and reinforcement strains (obtained using electrical resistance strain gages attached on concrete surface and steel bars) were registered. Figure 2 shows the locations were measurements were carried out. The rotations (twists) were obtained by subtracting the 2 deflections at each location and dividing by the horizontal distance between them.

3 MATERIALS

3.1 *Steel*

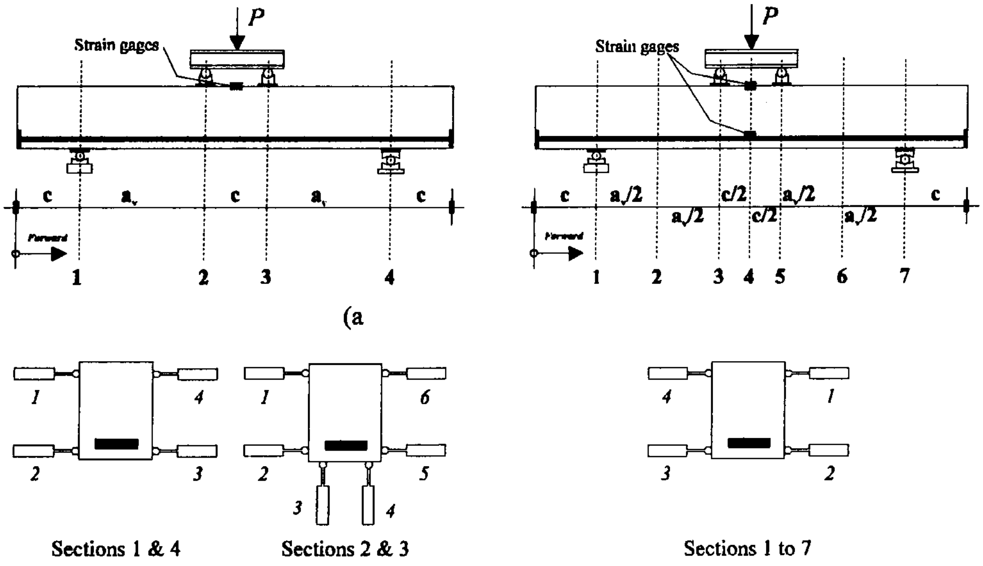
The characteristics of the ribbed steel employed are summarized in Table 1.

Table 1. Steel

Nominal diameter (mm)	Cross-sectional area (mm^2)	Yield stress (MPa)	Ultimate strength (MPa)
4.2**	14	768.0	807.1
6 *	28	572.0	733.9
12	113	570.8	714.6
16	201	436.6	702.7
20	314	458.6	765.9

* : stirrups of beam D1 & D2 (both series).

** : stirrups of beam D3 & D4 and long. reinforcement of beam D1 (both series).



(a

(b) T

Series 1 Series 2

Figure 2. Schematic representation of specimen's instrumentation

3.2 *Concrete*

The composition and strength properties of the concrete are indicated in Table 2. Because of the small dimensions of the involved beams, the maximum aggregate size was limited to 13 mm. Graduation of the maximum aggregate size in the same ratios as the dimension of the beams would be unrealistic because in actual practice large and smaller structural members are made with concrete containing the same large aggregate. The test cylinders were adjusted to suit the test beam sizes (70x150, 100x200 and 150x300 mm, respectively). The strength was found to vary slight with the size of the cylinder but the individual values do exhibit a considerable scatter. However, as the global results match with those obtained for Leonhardt & Walther (1961) from which the present experimental work was inspired, the results corresponding to the smaller cylinders were not used.

Table 2. Concrete

Series	1	2
Aggregates (%): 0 - 3 mm	29	29
3 - 7 mm	24	24
7 - 15 mm	47	47
Maximum aggregate size (mm)	13	13
Natural humidity (%)	1.8	0
Cement (Kg/m^3)	400	400
Water/cement ratio	0.40	0.40
Admixture (plastizicer) (%)	3	3
Average cylinder strength (MPa)		
at 28 days old	36.5	----
at moment of testing	37.3	39.7

4 TEST RESULTS

The outstanding test results are sumarized in Table 3.

Table 3. Results of experimental tests

Designation	Cracking Load	Failure						
		P_u	Q_u	τ_0	M_{su}	σ_{cu}	m_{su}	Avg.
	(KN)	(KN)	(KN)	(MPa)	(KNm)	(MPa)	(MPa)	(MPa)
D1/1	4.67	13.8	6.9	2.32	1.45	435	5.92	
D1/2	4.89	14.8	7.4	2.47	1.55	465	6.34	6.13
D2/1	11.4	52.5	26.3	2.21	11.0	409	5.61	
D2/2	12.5	51.5	25.8	2.16	10.8	403	5.52	5.57
D3/1	22.9	93.1	46.6	1.74	29.4	320	4.44	
D3/2	27.0	95.5	47.8	1.78	30.1	328	4.55	4.50
D4/1	38.0	147.5	73.8	1.55	62.0	277	3.95	
D4/2	37.5	179.0	89.5	1.88	75.2	336	4.79	4.37

4.1 *Cracks*

It was confirmed that with geometrically similar beams made with the same materials, the cracking patterns produced are also approximately similar. In all cases, the cracking patterns obtained strictly follow (in spite of the differences existing in the specimens) the patterns obtained in Stuttgart for Leonhardt & Walther (1961). Referring to cracking loads, it should be clearly realized that those mentioned in tests reports relate, not to the actual occurrence of cracks, but to their first visible appearance.

4.2 *The shear strength*

Once again, it is possible to recreate Leonhardt & Walther (1961) words: "As expected, all the beams failed by crushing of the shear compressive zone. This was associated with destruction of the bond --by horizontal cracks extending along the reinforcement from the shear crack to the bearing-- shortly before failure".

As it is shown in Figure 3, the ultimate loads exhibit large size effects. If they are represented using Bazant's type of diagrams (for a complete reference see: Bazant et al. 1994), it can be seen that they follow the law postulated for him. Unfortunately, the scatter exhibit in the results, although keeping into normal values, may disguise the actual magnitude of the reduction in the shear strength. As a comparison, it could be useful to refer to the last column of Table 3: the average value of the shear ultimate moments fall down from 6.13 for the smallest beam (D1) to 4.37 for the biggest one (D4).

4.3 *The out-of-plane actions*

As it was mentioned at the beginning, *unintended* out-of-plane actions were detected during testing under *intended* in-plane loads. The magnitudes of the transversal (horizontal) displacements measured were in the same order of magnitude as the vertical displacements. The vertical deflections assessed were between normal values and the P-Δ

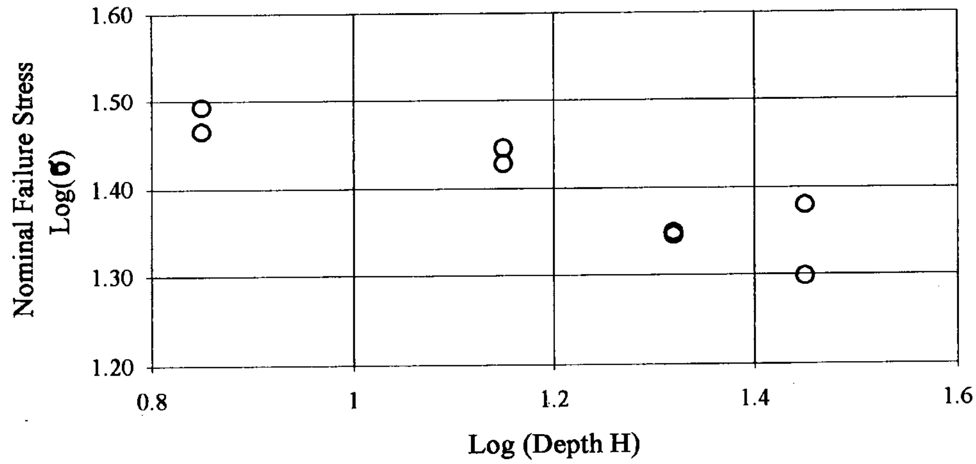


Figure 3. Bazant' representation of size effects in diagonal shear failure.

curves obtained had completely normal shapes (Ramallo et al. 1994). Nevertheless, out-of-plane actions were composed with rotational and translational displacements. Once the rigid body (translational) displacements were discounted, it was possible to assess the net twists underwent for the different monitored sections. With these comparable parameters evaluated in analogous section, P-Φ diagrams were carried out looking for any common feature lying in the curves (Ramallo et al. 1994). Unfortunately, the randomic nature of the observed phenomena disabled to recognize any repeated characteristic other than the always-ascending values of the twists even though the curves were very similar in shape for corresponding specimen of the different series.

However, in searching for a better suitable parameter to relate the detected out-of-plane actions with the size effect underlying the shear strength, the obtained twists were transformed in torsion stresses applying convenient torsion theories (Hsu 1984, Cowan 1965). Afterward, these stresses were represented in the same type of diagram (Figure 4) used for shear stresses following Bazant & Sener (1987). Surprisingly, and contrasting with the results that we were expecting for, also the torsion stresses followed the size effect postulated for Bazant (1984).

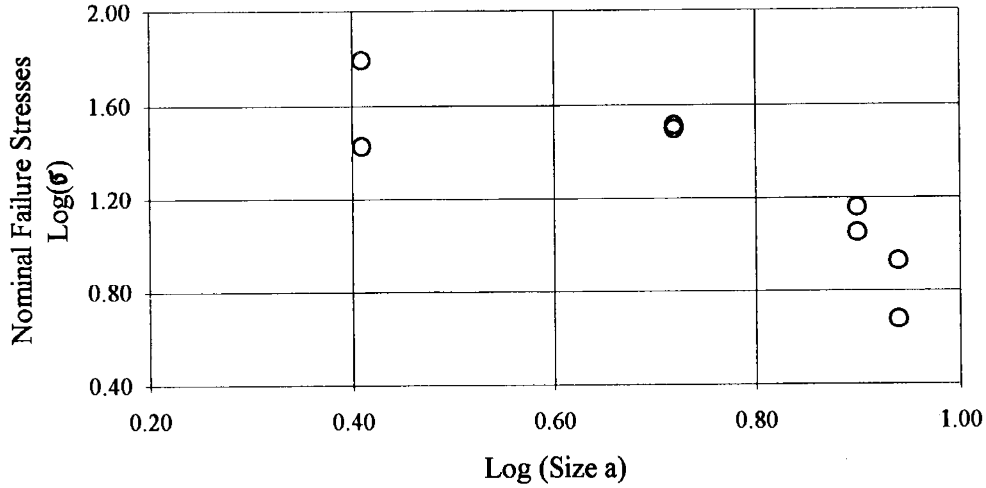


Figure 4. Size effect in torsion stresses due to unintended out-of-plane actions.

5 CONCLUSIONS

The presence of unintended out-of-plane actions of strong randomic nature was detected. Their implementations in computer-based analysis through any suitable parameters need a more complex analysis.

The existence of size effect on diagonal shear failure of beams without stirrups was verify. The correlation with the data from "The Stuttgart shear tests" (Leonhardt & Walther 1962) reinforces its validity.

From the observed tendency exhibit for the torsion stresses, it appears that the out-of-plane actions also follow the well-known Bazant's size effect law. Nevertheless, more experimental research is needed.

The most transcendental result attained with this experimental research is the gathering of a complete set of 4 series (16 specimens) of beams without stirrups with complete 3-D similarity. This set will enrich the scientific community that is always needing more experimental results.

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