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Experimental research of deformability of reinforced concrete elements with normal torsional cracks

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ABSTRACT:
The paper presents the results of experimental studies of deformability of reinforced concrete elements with normal cracks subjected to torsion. Normal cracks occur in elements of slab-ribbed systems at all stages of their operation. The paper shows the relevance of the proposed experimental research, since the stiffness of elements in torsion affects the redistribution of forces in reinforced concrete floor discs, which are characterised by spatial behaviour. The main characteristics of the deformability of experimental beams with normal cracks under torsional stress are presented. The results of experimental linear displacements of one beam block separated by an artificial crack relative to another are obtained. The dependences of linear displacements on torque at the stages of beam loading with torque are established. The dependences of displacements on torsional moments at different diameters of longitudinal reinforcement and at different heights of the cross-sectional zone without a crack are given.

KEYWORDS:
reinforced concrete; torsion; cracks

1. Analysis of publications and task statement

In reinforced concrete slabs, which are characterised by spatial behaviour, the redistribution of forces between their individual elements is affected not only by bending stiffness but also by torsional stiffness, as evidenced by a number of studies [1, 2]. Bending stiffness has been studied by many authors, while torsional stiffness has been the subject of a very limited number of theoretical and experimental works.

In particular, it was found that torsion occurring under compressed conditions increases the torsional stiffness of a rod with a solid or closed cross-section to a small extent, and with an open cross-section to a greater extent [3, 4].

The Central Research Institute of Commercial and Domestic Buildings has proposed a convenient and practical method for determining the torsional stiffness of ribbed slabs [5]. Its advantage is that it takes into account the physical nonlinearity of reinforced concrete both in bending and torsion. It has been determined [6] that the presence of holes in beams in bending with torsion affects the deformability of experimental specimens. With an increase in the height and length of the hole, the deformability of rectangular beams with through holes also increases.

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In general, most of the experimental and theoretical works are devoted to the study of the strength of reinforced concrete elements with cracks [7]. In the middle of the last century, Hornov's experimental studies established that the torsional stiffness of the edges of precast slabs of a floor cell changes due to crack formation, although spatial torsional cracks do not occur at all in areas remote from the supports.

In the existing scientific literature, there are practically no data on determining the torsional stiffness of reinforced concrete elements with normal cracks.

In addition to strength issues, these works consider the formation of cracks, their angles of inclination to the faces of the element, study different shapes of cross-sections, different ratios of bending and torque moments, the effect of strength characteristics of concrete and reinforcement, clamp spacing, and prestressing on the strength of reinforced concrete elements in torsional bending. Paper [4] and others report experimental studies of reinforced concrete beams and their deformations during testing. However, the issues of analysis of deformability and torsional stiffness are not considered.

An experimental study of torsional bending of beams with artificial transverse cracks is described in [8]. However, here, too, more attention was paid to the study of the strength characteristics of the specimens.

It is quite common for a reinforced concrete element to have a single reinforcement and only normal cracks. Such elements include the ribs of floor slabs. In a spatially deformed floor disc, these elements are subjected not only to bending but also to torsional moments.

Therefore, the purpose of this paper is to analyse the results of an experimental study of the deformability of rectangular reinforced concrete beams with normal cracks with the further prospect of developing a general methodology for determining the torsional stiffness of the above elements.

Researchers [4, 8] presented the theoretical foundations for determining stiffness and strength within the framework of the methodology for analysing a reinforced concrete beam element of rectangular cross-section with bending cracks. Paper [9] presents a detailed and expanded description of the methodology for determining the torsional stiffness of a reinforced concrete element with normal cracks. An iterative numerical analysis of a reinforced concrete ribbed slab based on the methodology given in [4, 8, 9] is given in [10].

2. Presentation of the main material

Reinforced concrete beams of rectangular cross-section with normal, artificially created cracks simulating cracks were tested at the production laboratory of Sumy Concrete Products Plant No. 1, Budindustriya.

The purpose of the experiment was to determine both the stiffness and strength characteristics of the specimens. Experimental reinforced concrete beam specimens with dimensions of 1000 mm × 200 mm × 120 mm were manufactured (Fig. 1).

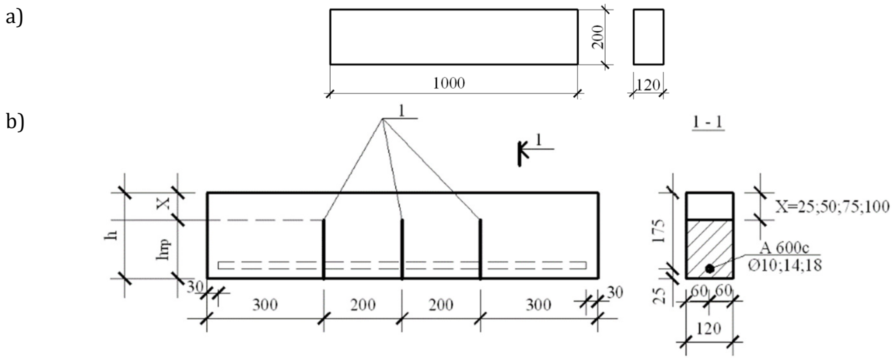

Fig. 1. Experimental beam: a) geometrical characteristics; b) beam division by normal cracks into separate blocks; reinforcement scheme of the specimens; 1 – chipboard insert

A total of 15 beams of five types were manufactured, with a single longitudinal rod made of A-600c class periodic reinforcement bars with diameters of 10.14 mm and 18 mm. There was no transverse reinforcement.

The beams were classified by type based on the height of the crack-free zone, and by subtype based on the diameter of the reinforcement. Beams of the fifth type were made without artificial cracks (Table 1).

Table 1
Marking of experimental beams

Height of the area without cracks x [mm]	Fitting diameter d_s [mm]	Beam grade
25	10	B 1-1
25	14	B 1-2
25	18	B 1-3
50	10	B 2-1
50	14	B 2-2
50	18	B 2-3
75	10	B 3-1
75	14	B 3-2
75	18	B 3-3
100	10	B 4-1
100	14	B 4-2
100	18	B 4-3
without cracks	10	B 5-1
without cracks	14	B 5-2
without cracks	18	B 5-3

The compression test of six cube specimens in accordance with [11] revealed that the concrete strength was 30.7 MPa. The modulus of deformation of concrete, obtained by testing eight prism specimens according to [12], was 32 097.5 MPa. According to the test data of reinforcement [13] of different diameters, the average yield strength of the specimens was 584.98 MPa.

A general view of the experimental setup with the sample is shown in Figure 2.

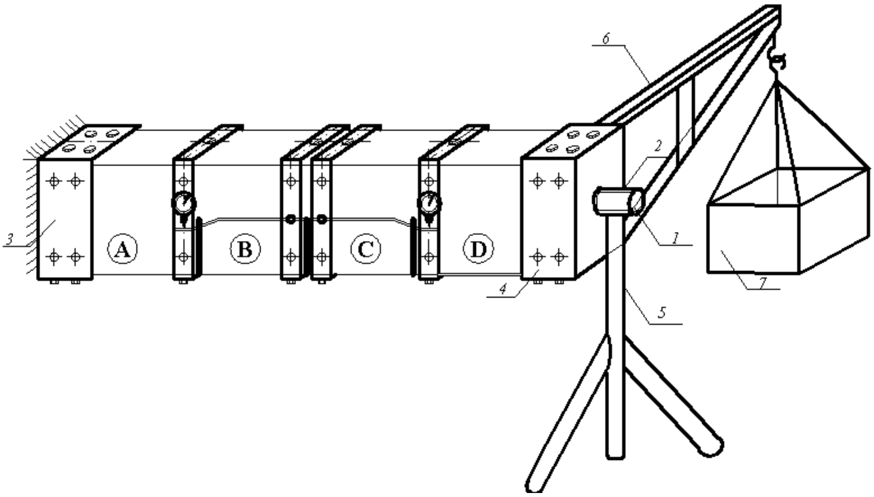

Fig. 2. Experimental installation: 1 – hinged shaft welded to the support box; 2 – bushing; 3 – box fixed rigidly; 4 – box with hinged support; 5 – support; 6 – lever; 7 – pallet with loads

The specimens were loaded in stages, with a load holding time of 10 minutes.

When studying the stiffness characteristics of specimens with normal cracks at the stages of their loading with a vertical load, the displacements of the two middle blocks B and C relative to the two outer blocks *A* and *D*, respectively, were measured using clock-type indicators (Fig. 2).

The experimental procedure for all beams was as follows:

- a specimen with four strip steel frames mounted on it was mounted in the supporting end boxes of the experimental setup. The ends of the specimen were bolted in the setup;
- the horizontal position of the specimen in the setup was checked; the frames were installed on the specimen and fixed with clamping bolts. A distance of 200 mm (measurement base) was maintained between the frames P-1 and P-2, P-3 and P-4, which was equal to the length of the block between the cracks;
- the distance from the legs of the ICh-1 and ICh-2 indicators to the side face of the beam was measured;
- the experimental beam specimens were loaded in stages with metal loads that were placed on a pallet and had approximately the same weight. All artificial loads were weighed and labelled in advance. The sample was kept under load for 10 minutes. The beams were loaded in stages until they were destroyed;
- the data of the blocks' displacements at the beginning and end of each loading stage were recorded in the logbook using clock-type indicators.

3. Research results

The beam specimens of the first series could not be considered suitable for research, since artificial normal cracks divided the specimen into separate blocks before they were installed in the experimental setup.

Table 2 and Figure 3 show the values of the experimental angle of rotation of the blocks separated by cracks for beams at a loading level of M_t = 0.2 kN·m. This level was chosen as the limit value of the external load at which the deformations remain elastic. In Table 2, *d* denotes the distance from the indicator leg to the central vertical axis of the beam cross-section.

Figures 4-6 show the torque-displacement relationship for beams with different compression zone heights at a fixed reinforcement diameter.

Table 2

Deformation and strength characteristics of experimental beams

Beam grade	Displacement a_{test}, (mm·10⁻²) at the level of M_t = 0.2 kN·m	Distance *d* [mm]	$\varphi = \frac{a_{test}}{d}$, 10^4 rad	Note
B 2-1	1.65	168.5	0.979	
B 2-2	1.45	170	0.853	
B 2-3	–	169	–	ν
B 3-1	1.59	170.5	0.933	
B 3-2	–	173.5	–	ν
B 3-3	1.23	169.5	0.726	
B 4-1	1.25	171	0.731	
B 4-2	1.15	166	0.693	
B 4-3	1.1	169	0.651	
B 5-1	0.99	169.5	0.584	
B 5-2	–	172.5	–	ν
B 5-3	1.04	170.5	0.610	

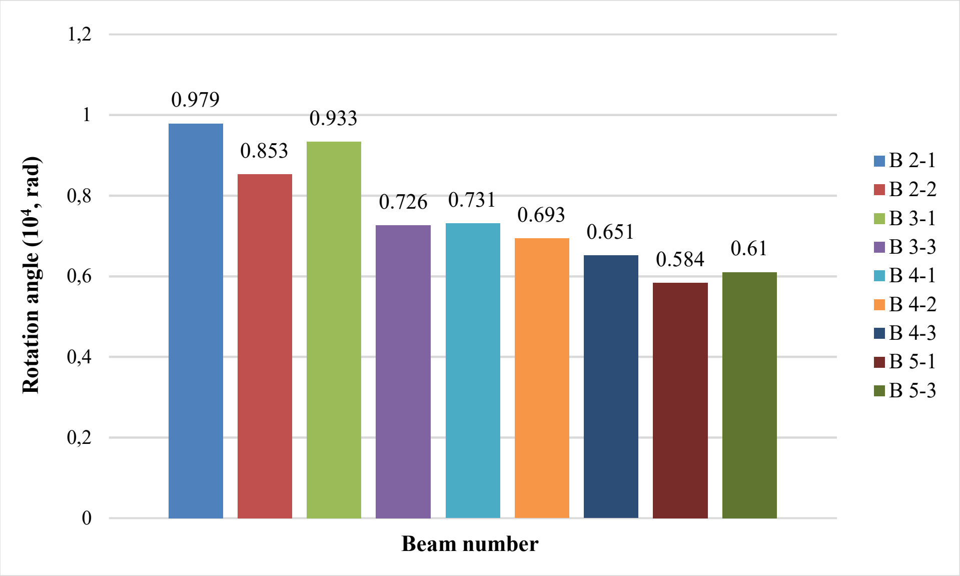

Fig. 3. Torsion angles for the experimental beams rotation angle (10^4, rad) at the level of M_t = 0.2 kN·m

In Table 2, the mark ν indicates the beams in which no reliable deformations were obtained in the experiment as a result of a violation of the rigidity of the fixing of the measuring devices.

Analysis of the dependences (Figs. 4 and 5) allows us to conclude that the operation of the experimental beams under pure torsion until the moment of failure was elastic in nature.

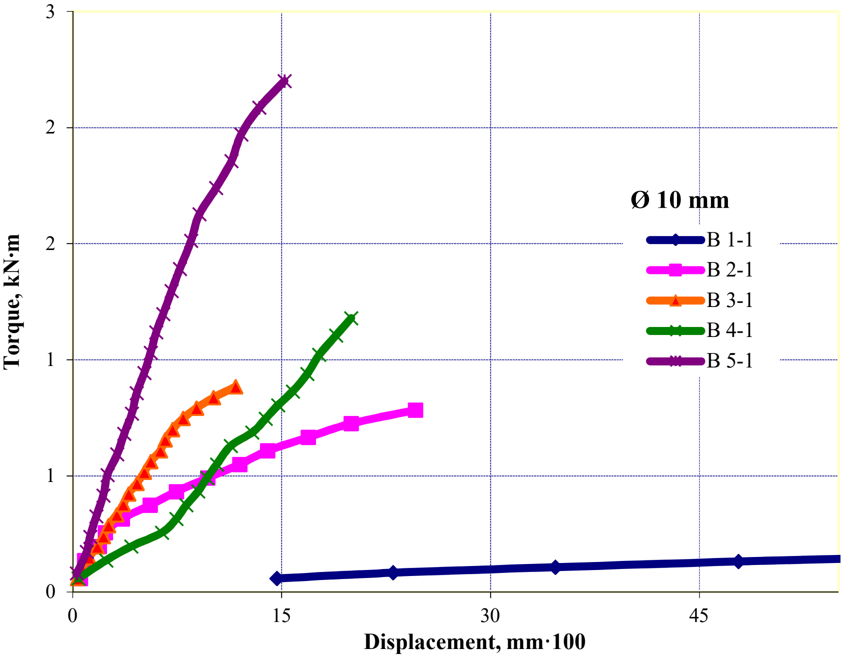

Fig. 4. Torque-displacement relationships for a longitudinal reinforcement diameter of Ø10 mm

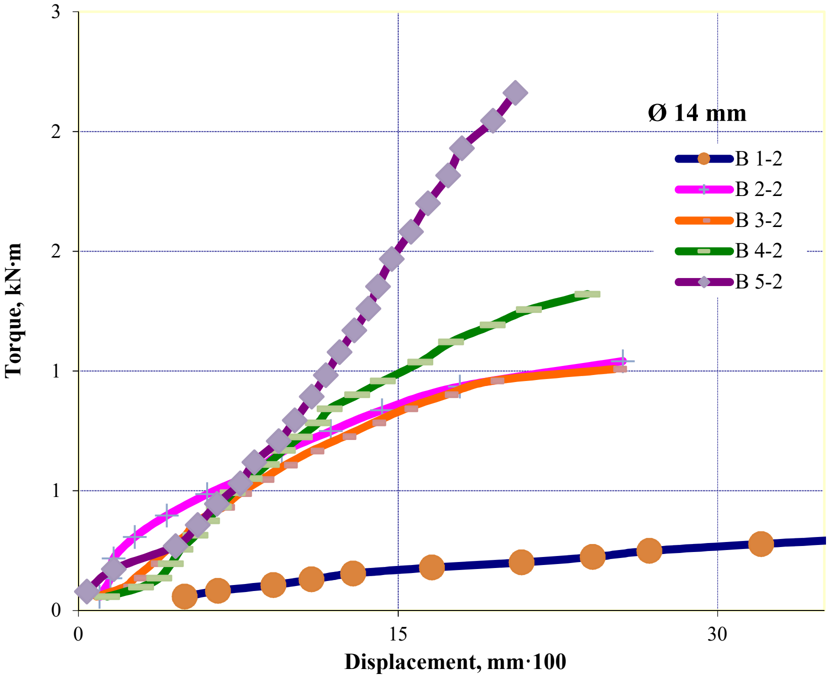

Fig. 5. Torque-displacement relationships for a longitudinal reinforcement diameter of Ø14 mm

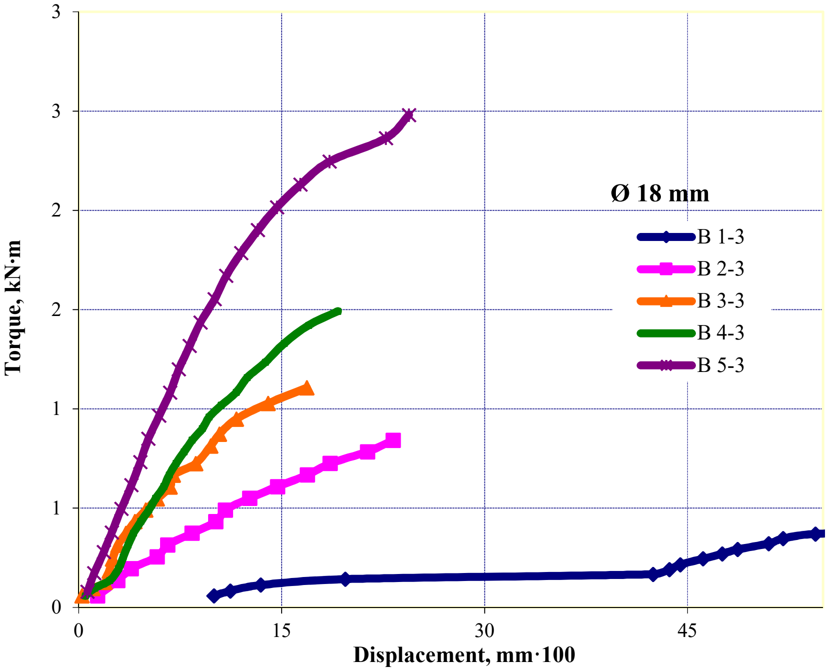

Fig. 6. Torque-displacement relationships for a longitudinal reinforcement diameter of Ø18 mm

Plastic deformations occurred at the last stages of loading of the specimens, immediately before their brittle fracture. Creep deformations of concrete, which occurred rapidly, were recorded using clock-type indicators (the arrow moved throughout the entire stage of the specimen's exposure to load), which indicated the approach of the moment of specimen failure. During the period when the movement of the indicator arrows did not stop, an inclined crack began to develop from the artificial normal crack in the upper part of the sample.

As the height of the crack-free zone in the experimental specimens increased, the torque-displacement relationship became more linear and the behaviour became more elastic. Similarly, as the diameter of the longitudinal reinforcement in the specimens increased, the behaviour of the beams also became more elastic. This effect is especially evident in beams reinforced with a longitudinal bar Ø18 mm (Fig. 5).

Thus, if we consider the dependencies shown in Figure 10, we can note that for beams of the fifth type (without cracks), the torque-displacement curves are almost linear.

Figures 7-10 show the torque-displacement relationship for beams with different reinforcement diameters at a fixed height of the compressed zone.

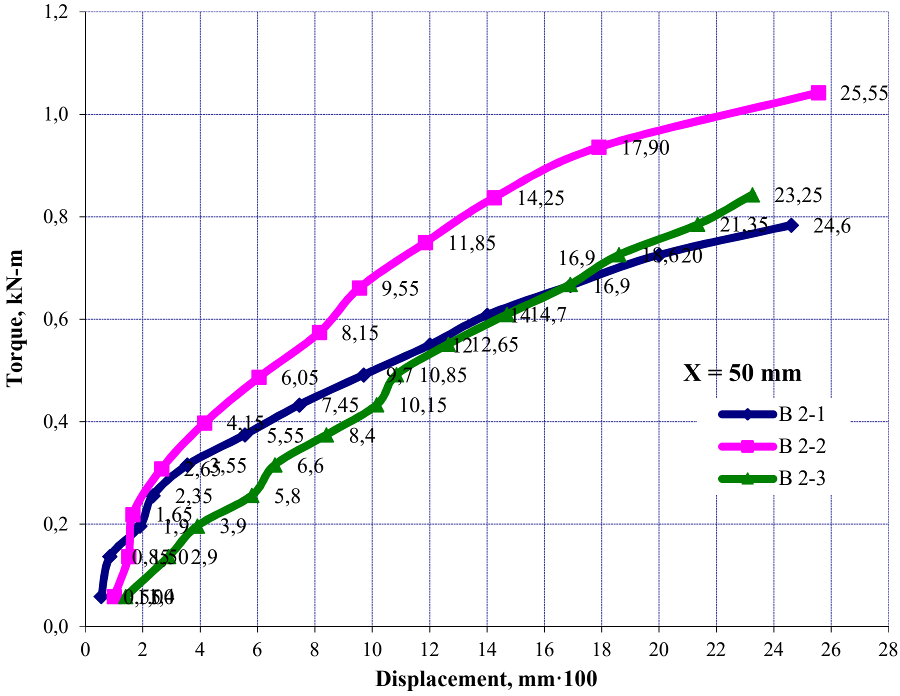

Fig. 7. Torque-displacement relationships at a compressed zone height of 50 mm

The nature of the fracture of all specimens was brittle, in the vast majority of cases – instantaneous; in some cases, the development and opening of a torsional crack in the compressed zone occurred within 0.5-1 minute. In the process of stepwise loading, up to the last stage, no cracks were observed on the beam faces, although the clockwork indicators that recorded the movement of the two middle blocks showed significant increases in deformation during the last stages of the sample's exposure to load.

The brittle and immediate nature of the failure is explained by the presence of only longitudinal reinforcement in the beams and the absence of transverse closed clamps. This explanation is confirmed by Cowan [14] and other authors.

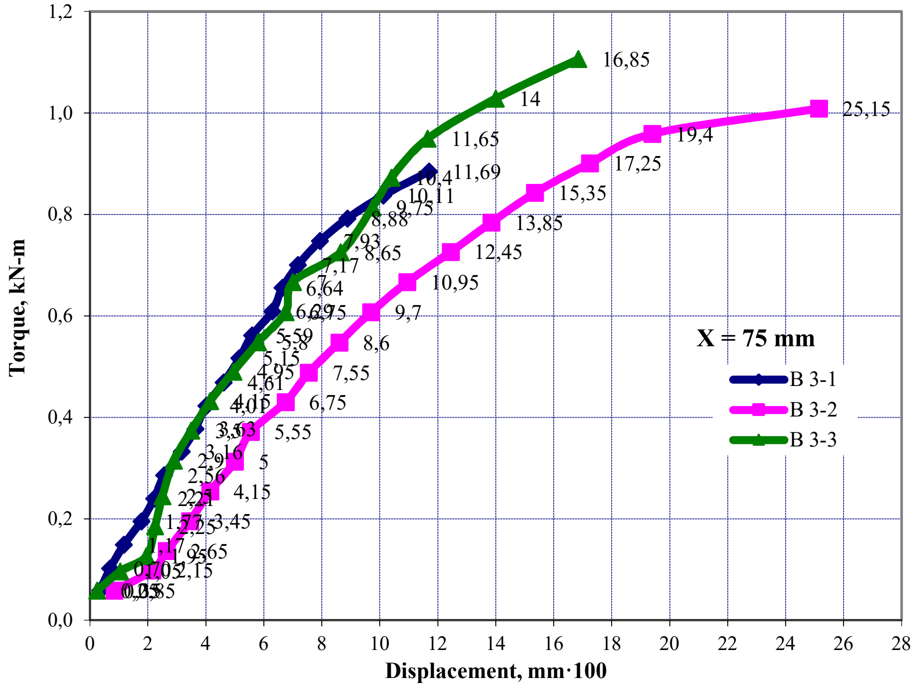

Fig. 8. Torque-displacement relationships at a compressed zone height of 75 mm

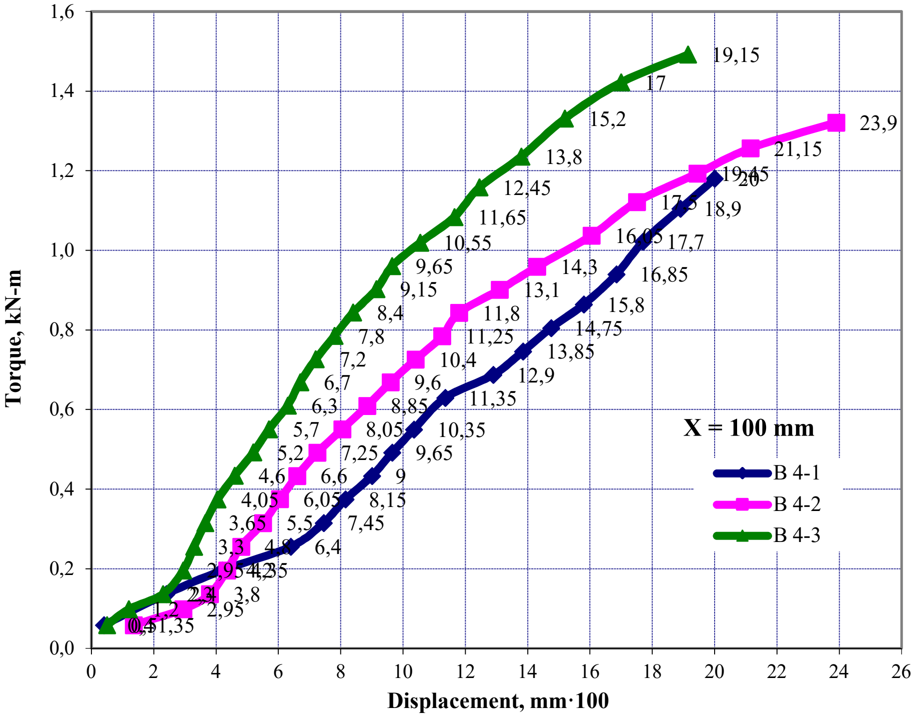

Fig. 9. Torque-displacement relationships at a compressed zone height of 100 mm

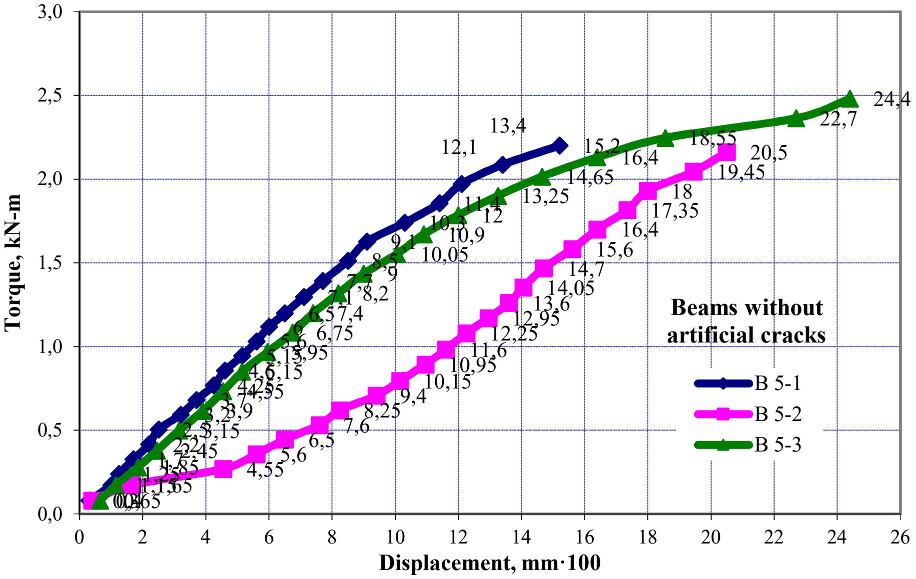

Fig. 10. Torque-displacement relationships for specimens without normal cracks

In all cases, the torsional crack started to develop on the lateral face in the crack-free area at an angle of 45º from the upper end of one of the three artificial normal cracks. The crack then propagated rapidly along the upper face, moving to the opposite side face. The crack developed, as a rule, along an open line. Thus, the failure of the beam occurred due to the appearance of a spatial torsional crack (Fig. 7) in the compressed zone, at a torque value equal to the limit.

For all experimental beams, the nature of the fracture was similar. Failure of the specimen occurred as a result of chipping [14]. This type of failure is characterised by a typical tear crack (Fig. 11) and is caused by an inclined tension arising from torsion.

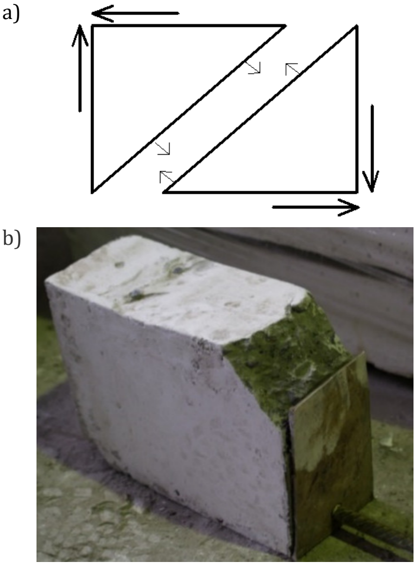

Fig. 11. General scheme of concrete fracture under the action of inclined tensile stresses (a); scheme of fracture along a spatial torsion crack in the compressed zone (b)

4. Conclusions and research perspectives

1. Reinforced concrete elements with normal cracks subjected to torsion have a diagram 'torque--displacement' of a curvilinear shape, which confirms the elastoplastic nature of the deformation of the specimens in torsion. Almost at the entire stage of torsional testing, the elastic component prevails in the deformations of the specimens. Plastic deformations are typical for the last stages of loading, which precede the fracture of the sample.
2. The main type of destruction is the destruction of the compressed zone from the action of inclined tension arising from the action of torsion.
3. As the height of the compressed zone increases and the diameter of the longitudinal reinforcement increases, the deformation behaviour of specimens with normal cracks reinforced only with longitudinal reinforcement approaches elasticity.
4. An increase in the diameter of the longitudinal reinforcement and the height of the zone compressed from bending leads to a decrease in deformation and an increase in torsional strength.

The **prospect of research is** to create a general method for determining the torsional stiffness of reinforced concrete elements of rectangular cross-section with normal cracks.

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Badania eksperymentalne odkształcalności elementów żelbetowych z normalnymi rysami skrętnymi

STRESZCZENIE:
Przedstawiono wyniki badań eksperymentalnych odkształcalności elementów żelbetowych z pęknięciami normalnymi poddanych skręcaniu. Pęknięcia normalne występują w elementach układów płytowo-żebrowych na wszystkich etapach ich eksploatacji. W artykule wykazano zasadność proponowanych badań eksperymentalnych, ponieważ sztywność elementów przy skręcaniu wpływa na redystrybucję sił w krążkach stropowych z betonu zbrojonego, które charakteryzują się zachowaniem przestrzennym. Przedstawiono główne charakterystyki odkształcalności belek doświadczalnych z pęknięciami normalnymi pod wpływem naprężenia skręcającego. Uzyskano wyniki eksperymentalnych przemieszczeń liniowych jednego bloku belki rozdzielonego sztuczną rysą względem drugiego. Określono zależności przemieszczeń liniowych od momentu skręcającego na etapach obciążania belki momentem skręcającym. Podano zależności przemieszczeń od momentów skręcających przy różnych średnicach zbrojenia podłużnego i na różnych wysokościach strefy przekroju poprzecznego niezarysowanego.

SŁOWA KLUCZOWE:
żelbet; skręcanie; rysy