UDC 624.012.45:539.413

EXPERIMENTAL STUDIES OF THE BENDING RESISTANCE OF COMPOSITE BEAMS WITH LOOP CONNECTIONS BETWEEN PRECAST PARTS

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Abstract

Loop connections for precast concrete structures have various advantages in terms of ease of setting, high flexibility and strength. Despite the advantages, the widespread use of the loop connection in the construction industry is limited due to the lack of a design methodology in performance standards. Several available design techniques outlined in various studies are empirical upper bound solutions based on experimental observations and results that do not take into account all the factors that affect loop connection behavior and strength. However, the influence of the main parameters of the loop connection cannot be ignored for detailed evaluation and decision making when designing these elements. In this regard, this article presents the results of experimental studies of prefabricated monolithic beams with loop connections on self-stressing concrete and concrete on Portland cement. The distinctive features that affect the load carrying ability and the fracture behavior of such elements when using expansive concrete and concrete on Portland cement as a monolithic connection are revealed.

Keywords: loop connections, bending resistance, expansive concrete, beam elements, failure mode.

ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ СОПРОТИВЛЕНИЯ ИЗГИБУ СБОРНО-МОНОЛИТНЫХ БАЛОК С ПЕТЛЕВЫМИ СТЫКОВЫМИ СОЕДИНЕНИЯМИ

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Реферат

Петлевое соединение для сборных железобетонных конструкций имеют различные преимущества, связанные с простотой установки, высокой гибкостью и прочностью. Несмотря на достоинства, широкое применение петлевого соединения в строительной отрасли ограничено из-за отсутствия методологии проектирования в нормативных документах. Несколько доступных методик к проектированию, изложенных в различных исследованиях, представляют собой эмпирические решения с верхней границей, основанные на экспериментальных наблюдениях и результатах, которые не учитывают все факторы, влияющие на поведение и прочность соединения. Тем не менее, влияние основных параметров петлевого соединения нельзя игнорировать для детальной оценки и принятия решения при проектировании данных элементов. В связи с этим, в данной статье представлены результаты экспериментальных исследований сборно-монолитных балок с петлевыми стыковыми соединениями на напрягающем бетоне и бетоне на портландцементе. Выявлены отличительные особенности, оказывающие влияние на несущую способность и характер разрушения таких элементов при использовании напрягающего бетона и бетона на портландцементе в качестве замоноличивания стыков.

Ключевые слова: петлевые соединения, сопротивление изгибу, напрягающий бетон, балочные элементы, характер разрушения.

Introduction

Loop connections of precast concrete structural elements have been the subject of research for several decades. Precast concrete buildings experience significant damage during earthquakes, which is mainly concentrated around the joint areas due to inadequate connection systems that tend to loosen during ground movement [1]. Inadequate anchoring between precast concrete elements has been found to be a major source of damage during several earthquakes around the world. The structural behavior of precast concrete elements is determined by the mechanism and resistance of the connections, which requires adequate load transfer and ductility. Often the connections between precast concrete elements are embedded with concrete without any mechanical connection, which leads to a gap between the precast parts of the structure, which in turn affects the performance of the structure due to partial load transfer [2–4]. Thus, mechanical connection is inevitable to achieve the monolithic behavior of the precast concrete system. The reinforcement of precast concrete elements sometimes itself acts as a mechanical connection, with the reinforcement of two precast concrete elements being connected in place [5].

Loop connections (U-shaped bars) are common in the construction industry and are widely used to connect precast concrete elements where the rebars are 180° bent, forming U-shaped bars, which are spaced apart to ensure transmission of forces.

There are many studies on the behavior of a loop connection under tensile and bending loads, but there is no systematic approach to its design, as well as studies related to the use of self-stressing concrete as a monolithic loop connection. In the light of the foregoing, this paper presents results of the experimental studies based on static tests of composite beams with a loop connection on self-stressing concrete and OPC concrete under the action of a bending, as well as their comparative analysis.

Experimental investigation

Test specimens. Despite of significant amount of experimental and theoretical studies of loop joints both in tension and in bending [6–11], there are still no studies that would study the effect of self-stressing concrete on the stress-strain state of such elements under the action of a static load. The creation of an initial stress-strain state at the expansion stage of the self-stressing concrete of the loop connection can contribute to an increase in the crack resistance (stiffness) of the connection. Most of the known analytical models for calculating the resistance of loop connections are based on the results of experimental studies, so they are not able to take into account the initial stress-strain state obtained at the expansion stage of self-stressing concrete.

Based on the foregoing, experimental studies of the bending resistance of loop connections on self-stressing concrete and OPC concrete were carried out.

As experimental specimens, composite beam elements of rectangular section with dimensions b x h = 150 x 200 mm and a length of 2370 mm with stirrups in the prefabricated parts of the beams were made and tested. These beams were formed in two stages:

1) Precast parts of composite beams with length of the 1010 mm with loop connections from reinforcement Ø10 S500 were made (see Figure 1a).
2) After 28 days of concreting the precast parts of the beams, the two halves were assembled and the loop connections 350 mm width were cast in place using self-stressing concrete and concrete on Portland cement (see Figure 1b).

The construction of the experimental beams is shown in Figure 1.

A total of 10 test beams were casted (5 beams with loop connection filled with OPC concrete and 5 beams with loop connection filled with self-stressing concrete).

doi.org/10.36773/1818-1112-2022-129-3-20-26

Experimental beams with the loop connection on OPC-concrete were made without transverse reinforcement in the connections themselves (position 3 in Figure 1b).

The demolding of the experimental beams and control samples was carried out after the concrete had gained demolding strength (average compressive strength f_{cm}=11 MPa). The curing the of experimental beams and control samples took place for 28 days in moist conditions (control samples made of expansive concrete and loop connections of beams were moistened every day).

The measurement of the longitudinal deformations the looped joint in the experimental beams at the stage of hardening and the expansion of the self-stressing concrete in moist curing conditions was made with usage of the electronic an indicators with a division value of 0.001 mm on the base of 600 mm (when measuring deformations along the lateral boundaries of the experiment of the beam). On each beam, 4 benchmarks were installed on the top and bottom reinforcement (in the middle section of the span (cast-in-place part of the beam). Figure 2 shown the arrangement of the deformometers on the experimental beam.

The testing of the experimental beams was carried out with usage one hydraulic jack (load capacity 250 kN) after the concrete of the loop connection had gained at least 28-day strength. The load to the experimental beam was applied through the traverse at two points according to the scheme - a simply supported beam loaded with two forces. Such an arrangement of the hydraulic jack was adopted in order to obtain a zone of pure bending in the looped joint of the precast part of the beam. Test schemes for experimental beams are shown in Figure 3.

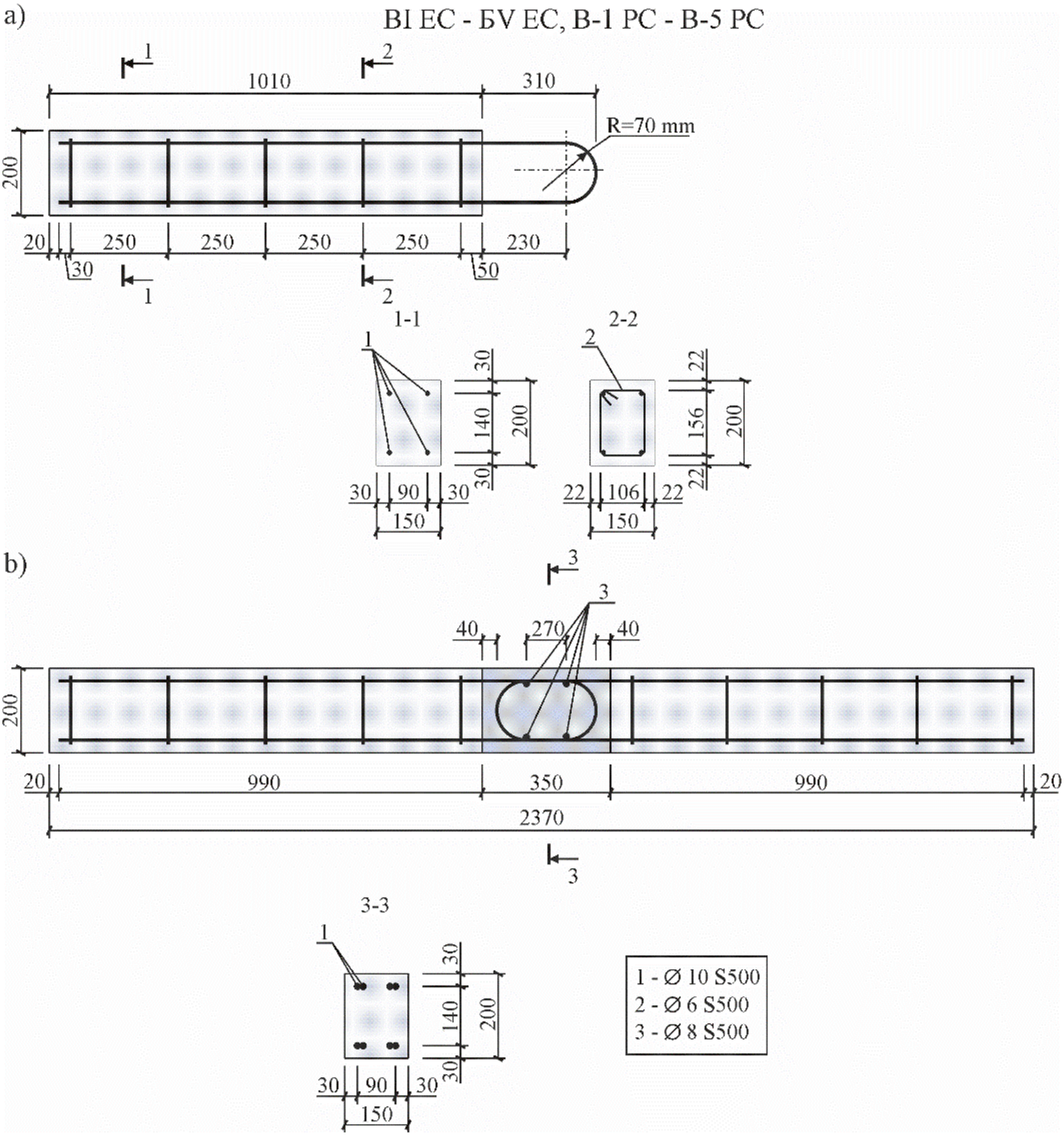


Figure 1 – Construction of experimental precast and cast-in-situ beams

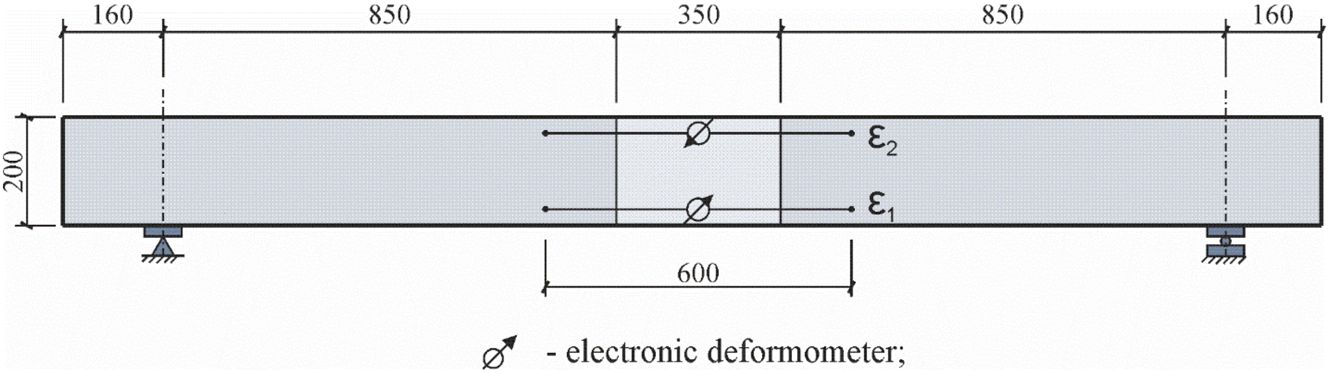


Figure 2 – Scheme of benchmarks arrangement on an experimental beam for measuring deformations at the self-stressing stage of concrete of a loop connection (BI EC – BV EC)

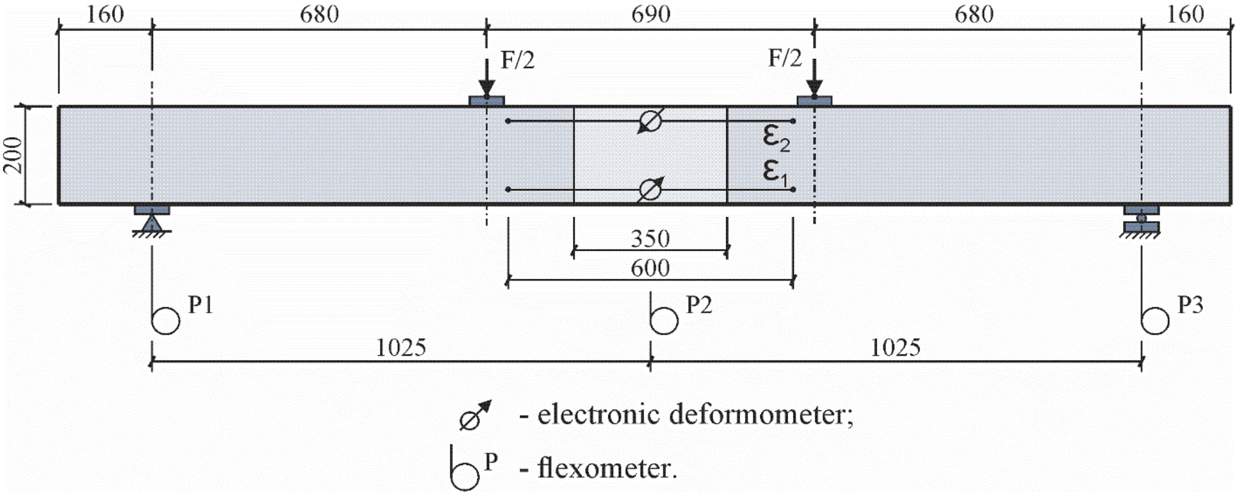


Figure 3 – Scheme of loading and arrangement of measuring instruments during static testing of experimental beams

Reinforcement

The reinforcement of the experimental beams was made with steel bars (Ø10 S500). As a stirrup of the precast parts of the beams, steel bars Ø6 S500 were used to create a spatial frame. Steel bars Ø8 S500 (beams BI EC – BV EC) were used as transverse reinforcement of the loop connections. Properties of reinforcement are presented in table 1.

Table 1 – Properties of reinforcement

Strength grade	Diameter Ø, mm	Yield stress level, MPa	Modulus of elasticity E_sx10^3, MPa	Position in figure 1
S500	6	587,1	200	2
	8	616,7	200	3
	10	649,4	200	1

Concrete

The selection of the nominal concrete composition was adopted taking into account the achievement of self-stress (except for the composition of beams B-1 PC – B-5 PC).

To achieve self-stressing of concrete, expanding additives CSA 20 were used (loop joint of beams BI EC – BV EC). The concrete mixture was prepared in a revolving-drum concrete mixer, followed by casing in the formwork and compaction with a deep vibrator.

Tables 2 and 3 resent the values mechanical properties of concrete, which was utilizing to casting of experimental beams. These results were obtained by the testing standard specimens at the time immediately before the loading.

Table 2 – The main properties of the concrete of the precast parts of the beams

Element	Beam signification	$f_{c,cube}$, MPa	$f_{cm,\ cyl}$, MPa	E_{cm}, GPa
Concrete of the precast parts of the experimental beams	BI EC, BII EC, B-1 PC – B-5 PC	28,9	21,3	31,5
	PIII EC – BV EC	34,8	30,6	35,0

Notes. $f_{c,cube}$, – mean cube compressive strength; $f_{cm,\ cyl}$, – mean concrete compressive strength based on cylinders (Ø150, h=300mm).

Table 3 – The main characteristics of concrete loop connections at the time of static testing

Element	Beam name	$f_{c,cube}$, MPa	$f_{cm,\ prizma}$, MPa	$f_{cm,\ cyl}$, MPa	E_{cm}, GPa	Free Linear Expansion, λ, %	Self-stresses, $f_{CE,k}$, MPa
Concrete loop connections	B-1 PC – B-5 PC	37,1	30,7	25,0	32,1	–	–
	BI EC – BV EC	29,9	59,1	16,6	34,1	0,95	2,8

Notes. $f_{cm,\ prizma}$ – mean concrete compressive strength based on prisms hardened under conditions of elastic restraint (100x100x400mm); $f_{cm,\ cyl.}$ – mean concrete compressive strength based on cylinders hardened without axial elastic limitation (Ø150, h=300mm); $f_{CE,k}$ – mean self-stresses grade based on prisms (100x100x400mm); $\varepsilon_{CE,f}$ – strain free expansion based on cylinders (Ø150, h=300mm).

Results obtained from experimental studies

Based on the value of the fixed longitudinal deformations by the time of the static test, the self-stress values of the concrete of the loop connection (beams BI EC – BV EC) were determined, which are presented in Table 4.

The cracking loads and failure loads recorded during static tests are presented in tables 5 and 6.

Table 4 – The values of self-stress at the moment of stabilization of the expansion

Beam designation	The values of self-stress σ_{CE}, MPa
BI EC	1,69
BII EC	1,44
BIII EC	1,85
BIV EC	2,05
BV EC	2,05

Table 5 – Results of static tests of composite beams with a self-stressed loop joint

Beam designation	$F_{cr}/2$, kN	M_{cr}, kN·m	$F_u/2$, kN	M_u, kN·m	Failure mode
BI EC	4,90	3,33	24,85	16,90	Compressed concrete failure in the precast part of the beam
BII EC	4,90	3,33	24,80	16,86	
BIII EC	7,40	5,03	25,10	17,07	
BIV EC	7,40	5,03	24,05	16,35	
BV EC	7,40	5,03	23,90	16,25	

Notes. $F_{cr}/2$ – cracking load; M_{cr} – cracking bending moment; $F_u/2$ – failure load; M_u – failure bending moment.

Table 6 – Results of static tests of composite beams with looped joint on OPC- concrete

Beam name	$F_{cr}/2$, kN	M_{cr}, kN·m	$F_u/2$, kN	M_u, kN·m	Failure mode
B-1 PC	2,40	1,63	22,40	15,23	Crushing of the concrete core inside the loop (loop connection area)
B-2 PC	2,40	1,63	22,40	15,23	
B-3 PC	2,40	1,63	21,40	14,55	
B-4 PC	2,40	1,63	22,05	14,99	
B-5 PC	2,40	1,63	23,30	15,84	

Composite beams with looped joints filled by the self-stressing concrete (beams BI EC – BV EC). The first flexural cracks appeared in all beams under load equal 0.2..0.31 $F_{tot,u}$. It should be noted that the first cracks developed simultaneously in the precast parts and cast-in-suit concrete of the beam. Flexural cracks were distributed in near the same distance along the length of the beam span. Depth of the cracks observed about 50% of the height of the cross-section. It should be noted that in the cast-in-suit part (in the zone of the looped joint of the beam), cracks at the time of formation developed to a bottom part of the beam section (up to 15-20% of the height of the beam cross-section).

Cracks at the contact of precast parts and cast-in-situ concrete in all beams were formed at a load equal to ≈0.4 $F_{tot,u}$. (except for beam BII EC (≈0.3 $F_{tot,u}$.)), which may indicate the presence of compressive stresses at the contact between precast and monolithic parts which are formed at the stage of concrete self-stressing in the loop joint. It should be noted that these cracks, as the load increased, developed along the compressed reinforcement.

Cracks width at the contact of the precast and monolithic parts of the beam under the applied loads had the largest value during static tests and under load close to the ultimate, the crack opening exceeded w_u=1,7 mm.

As the load increases, cracks developed and achieved near 88% of the cross-section height in all experimental beams.

The failure of all experimental beams occurred by the crushing of the compressed concrete in the precast part (under the applied concentrated force).

Self-stressing concrete contributes to the creation of the initial stress-strain state, which, in turn, affects the behavior of the beam during static tests.

Composite beams with looped joint filled with OPC-concrete (beams B-1 PC – B-5 PC). The first flexural cracks developed in all beams under load equal 0.10..0.11$F_{tot,u}$. It should be noted that the first cracks developed at the contact of the precast and monolithic parts of the beam, which at the time of formation reached 60..86% of the cross-section height. Cracks were distributed along the length of the span with approximately equal steps (see Figure 5). At the moment of formation cracks reached 15..50% of the height of the cross-section. It should be noted that in the monolithic part (in the zone of the looped joint of the beam), cracks at the time of formation developed to a lower height of the beam cross-section (up to 20-50% of the height of the beam cross-section).

As the load increased, cracks at the contact of precast parts and monolithic part in all beams (except for B-3 PC) developed along the compressed reinforcement.

As the load increased, cracks reached approximately 90% of the cross-section height in all experimental beams.

It should be noted that the critical crack was formed as a flexural crack outside the section of the direct insertion of the looped joint. As the load increased, the critical crack went around the looped joint on both sides of the joint. A compressed core is formed inside the loop connection, and the connections transfer tensile forces to the precast parts of the beam.

At the same time, this crack width is related with yielding of the reinforcing bars. However, this was not considered in the experiments. It should be concluded that the width of the crack opening increases due to the compliance of the concrete core enclosed within the loop. The failure of all experimental beams occurred when the concrete core was crushed inside the loop (looped joint).

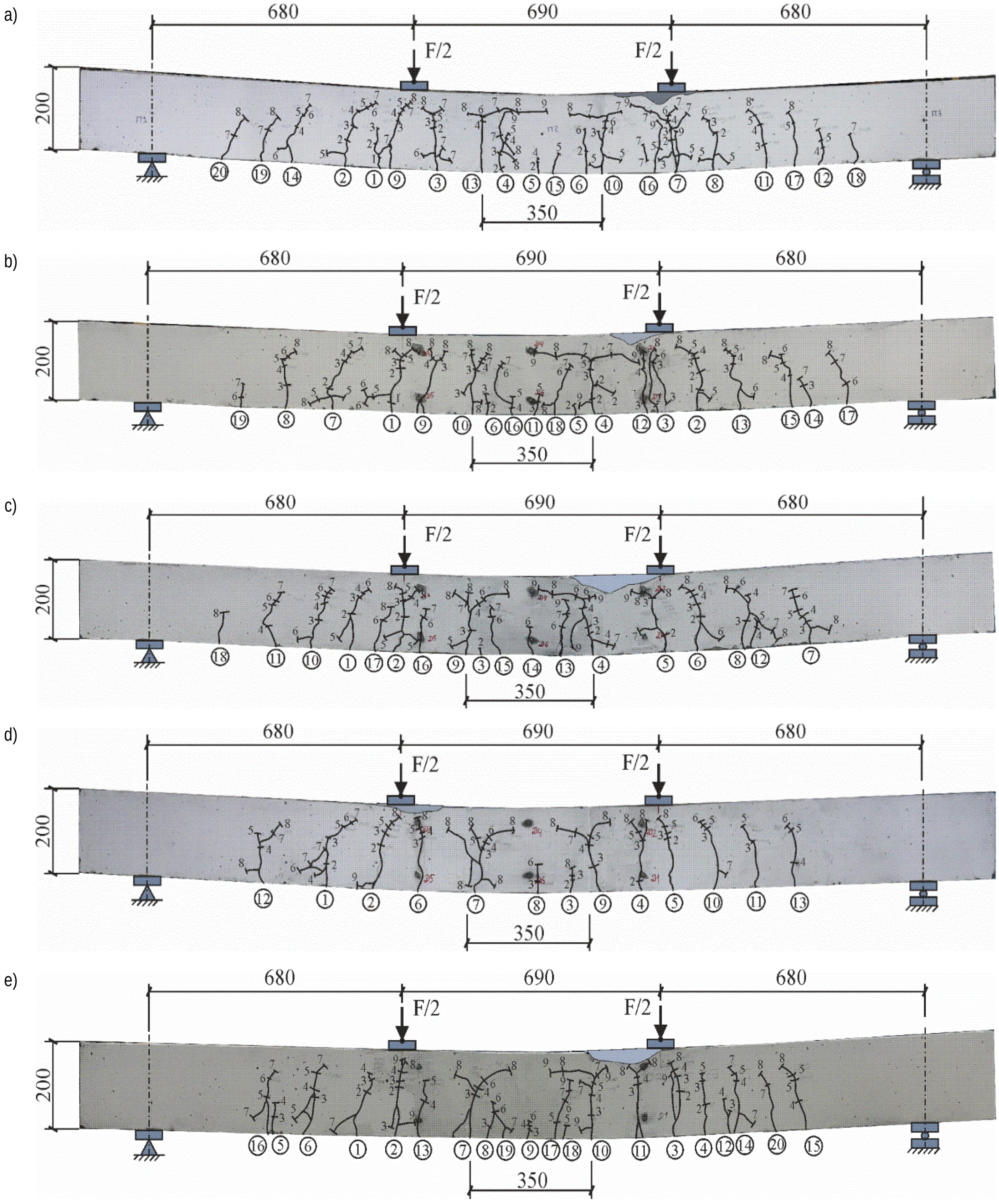
Differences in the behavior of precast and cast-in-suit beams with a loop connection on expansive concrete and concrete on Portland cement under the action of bending loads

The results of experimental tests are stable and repeatable. This conclusion is based on the fact that practically unchanged positions of the sections were observed in which flexural cracks were formed and the trajectories of their development (see Figures 4 and 5).

Based on the results of experimental studies of precast and composite beams with a looped joint on self-stressing concrete and OPC-concrete, a comparative analysis of the bending resistance and stiffness characteristics of these beams, recorded under the action of bending loads, was carried out. The results of comparison of deflections and relative deformations of tensile reinforcement and compressed concrete recorded in the course of static tests of all experimental beams are shown in Figures 6 and 7, respectively.

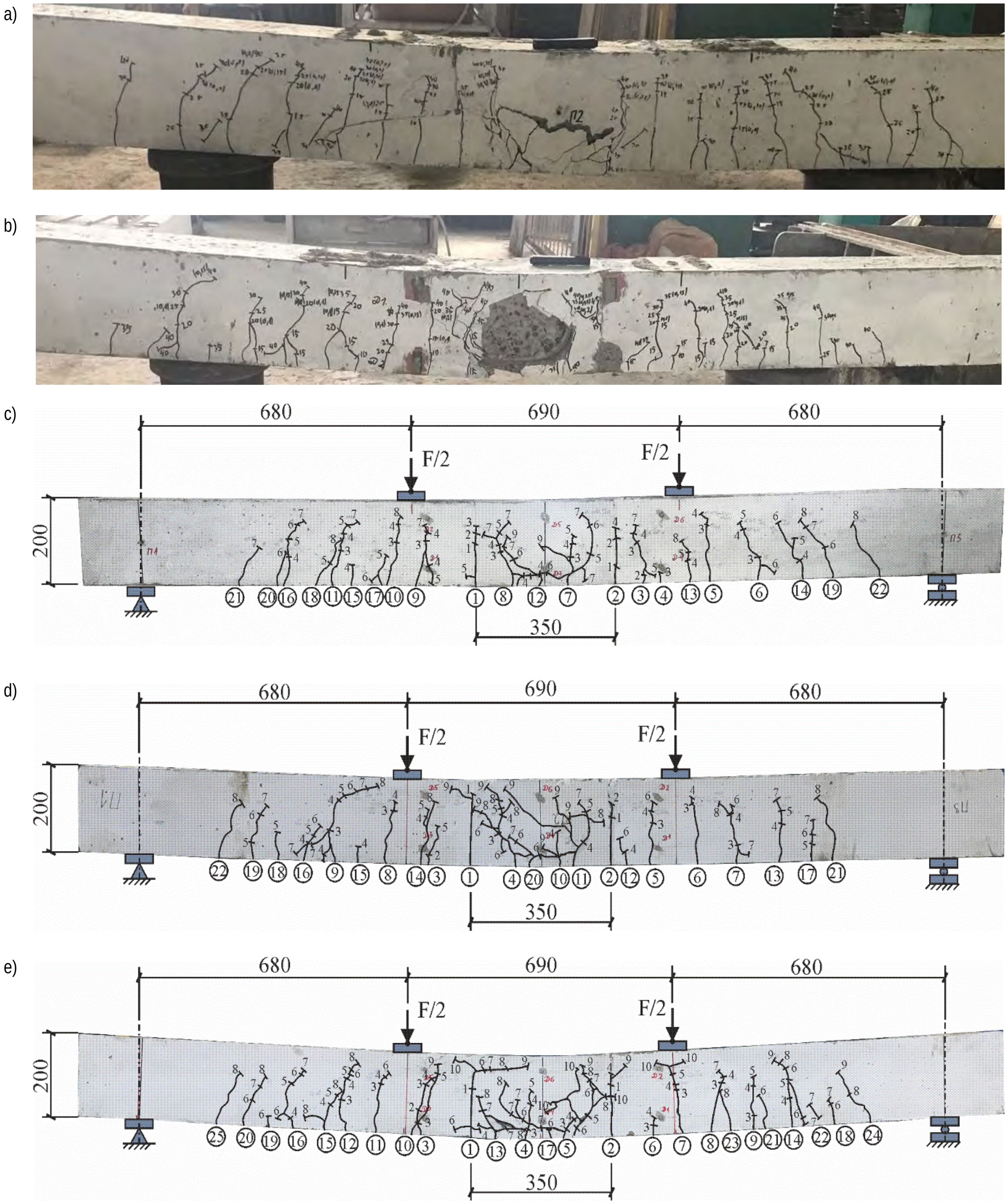
Based on the results of the comparative analysis presented in Figures 6 and 7, all experimental beams demonstrated the same behaviour at the initial stages of loading. However, composite beams with a looped joint filled with self-stressing concrete have a greater resistance (see Tables 5 and 6) and a lower bending stiffness under the ultimate load, compared with beams with a looped joint filled with OPC-concrete. Also, the usage of expansive concrete for filling of the looped joint increases crack resistance.

It is worth noting that precast and cast-in-suit beams with a loop connection on self-stressing concrete failed against the compressed concrete in the precast part (see Figure 4), while the failure of identical beams with a loop connection on Portland cement concrete occurred as a result of crushing of the concrete core inside the loop (see Figure 5).



a) – beam BI EC; b) – beam BII EC; c) – beam BIII EC; d) – beam BIV EC; e) – beam BV EC

Figure 4 – Cracks patterns for composite beams with a self-stressed loop joint



a) – beam B-1 PC; b) – beam B-2 PC; c) – beam B-3 PC; d) – beam B-4 PC; e) – beam B-5 PC

Figure 5 – Cracks patterns for composite beams with looped joint on OPC- concrete

Based on the results of the comparative analysis presented in Figures 6 and 7, all experimental beams demonstrated the same behaviour at the initial stages of loading. However, composite beams with a looped joint filled with self-stressing concrete have a greater resistance (see Tables 5 and 6) and a lower bending stiffness under the ultimate load, compared with beams with a looped joint filled with OPC-concrete. Also, the usage of expansive concrete for filling of the looped joint increases crack resistance.

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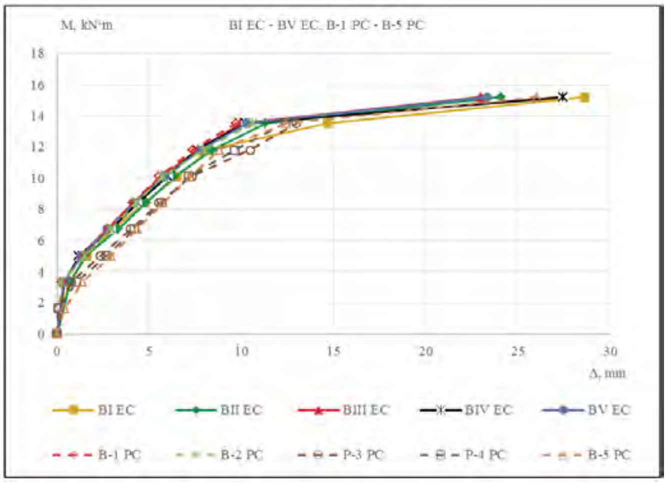

Figure 6 – Relation "moment – deflection" for tested beams (beams BI EC – BV EC, B-1 PC – B-5 PC)

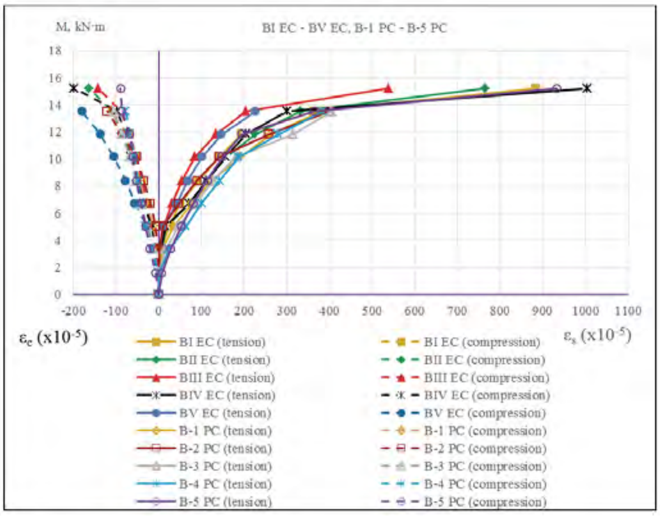

Figure 7 – Relation "moment – strains" for tested beams (beams BI EC – BV EC, B-1 PC – B-5 PC)

Conclusion

This paper presents the results of experimental studies of the bending resistance of the composite beams with a looped joints filled by self-stressing concrete and OPC-concrete. After analyzing the results of tests of beams under the action of a bending moment, as well as investigating the effect of self-stressing concrete of a looped joint on cracking and bearing capacity, we can draw the following preliminary conclusions:

1. The use of looped joints makes it possible to ensure the joint operation of individual precast parts of elements in a fairly wide range of loading.
2. The difference between the use of self-stressing concrete and concrete on Portland cement as a monolithic loop connection of composite beams is the failure mode. Self-stressing concrete contributes to the creation of a single structure consisting of precast parts with looped joint. This conclusion is confirmed by the fact that the failure occurs by the crushing of the compressed concrete of precast parts of elements, while the failure of composite beams with a looped joint filled with concrete on Portland cement occurs by crushing the concrete of the compressed core enclosed between the loop connections. It should be noted that the deformability and strength under the action of a bending moment in loop connections on expansive concrete is higher than on concrete on Portland cement.

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Accepted 04.11.2022