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STRENGTHENING OF CONCRETE ELEMENTS BY PRESTRESSED COMPOSITE STRIPS

Представлено результати досліджень з метою демонстрації можливості і практичних переваг, що походять від додатка напруженої композиитної смуги (вуглецеве армоване полімерне волокно), щоб підсилити бетонні конструкції. Розповсюдження напружень зрізу у клейовому з'єднанні було визначено на підставі теоретичного аналізу рівноважного стану. Запроектовано систему напруження смуги CFRP і зміцнення напружених балок. Балку перевірено під статичними і динамічними навантаженнями. Наведено результати випробувань і висновки, що ґрунтуються на них.

Ключові слова: CFRP, бетонні конструкції, напруження зрізу, напружені балки.

The paper presents the results of research aiming at exposing the possibility and practical advantages resulting from the application of stressed composite strip (Carbon Fibre Reinforced Polymer) to strengthen concrete structures. The distribution of shear stress in the glue joint was determined on the basis of theoretical analysis of equilibrium state. This knowledge allowed the system of stressing CFRP strip and strengthening the prestressed girder to be designed. The girder was tested under static and dynamic loads. The paper presents the results of tests and conclusions based on them.

Keywords: CFRP, concrete structures, shear stress, prestressed girder.

1. Introduction. In bridge strengthening, high tensile strength of composite strip CFRP was utilized in small degree [1, 2, 3] till now. Composite strips are characteristic by very large range of linear strain, reaching the value of 1.8%. The allowable extension of the glued composite element is the decisive parameter to the way of its utilization and cost effective application of this type of reinforcement. Hence the endeavours to apply composite strip in the stressed state [4, 5, 6,7].

Strip pre-tensioning allows taking fuller advantage of its capacity and the resulting increase of economic effectiveness of the reinforcement [8, 9, 10, 11]. Pre-tensioned composite strip reinforced with carbon fibre (CFRP) gives new possibilities of strengthening existing structures. Thanks to stressing, the bonded CFRP strip takes an active part in carrying dead loads imposed on structure and causes stress reduction in the inner reinforcement [12, 13, 14]. The anchorages take an important part of the delaminating force and diminish radically shear stresses in the glued joint, particularly at strip ends [15, 16, 17]. Proper design and effective use of stressed composite strip requires analytic and empirical investigation of inner force distribution (stresses) in the strengthened structure and especially shear forces prevailing in the glued joint.

2. Analysis of equilibrium in the joint of the glued, tensioned element

2.1. Condition taking no account of bending moment influence

Shear stress in the joint is analyzed taking account of elastic theory assumptions. To simplify, linear model is assumed. This means that that pure shear is acting in the joint and the width of the strip is unity (Fig. 1).

Further, following assumptions are adopted:

- the materials (beam of length *l* and depth *h*, bonded element of thickness *t* and the glue, all having Kirchhoff's coefficient of rigidity *G*) are homogeneous, isotropic and linear elastic,
- the glue is transmitting shear forces only,
- glued joint thickness equal *s,* is constant over the entire surface of the bond,
- the width of joint is constant over the entire length,
- the effect of bending moments is neglected.

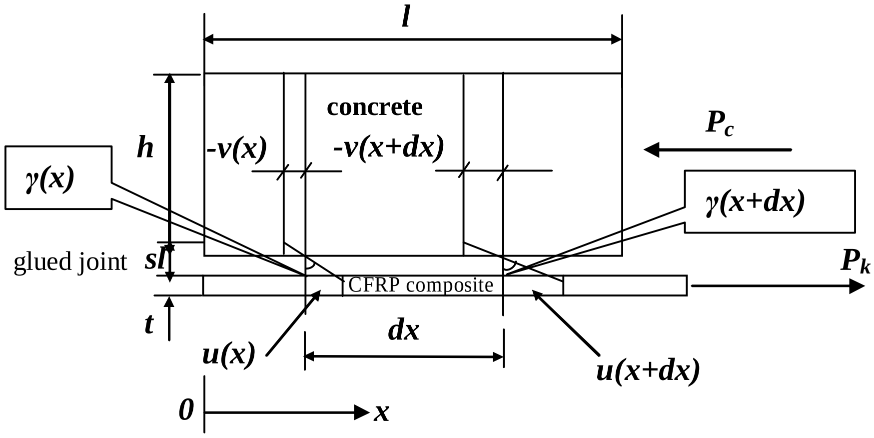

Fig. 1. Theoretical model of glued joint transmitting pure shear

Assuming :

Boundary conditions in the form :

(1) $P_k(x) = P_c(x) = 0$ *if* $x = 0$,

(2) $P_k(x) = P_k(l)$ *if* $x = l$

$$\text{and:}\quad e^{wx} + e^{-wx} = 2\cosh(wx)\,, \tag{1}$$

$$\text{where:}\quad w = \left[\frac{G}{s}\left(\frac{1}{E_k t} + \frac{1}{E_c h}\right)\right]^{1/2}, \tag{2}$$

E_c – modulus of elasticity for concrete, E_k – modulus of elasticity of the bonded element (composite) we can write :

$$t\,(x) = wP_k\,(l)\frac{\cosh(wx)}{\sinh(wl)}\,, \tag{3}$$

If we assume that shear force distribution is constant over the width b_k of the glued (composite) element, then it can be written :

$$t\,(x) = w\,\frac{P_k\,(l)\cosh(wx)}{b_k\sinh(wl)}\,. \tag{4}$$

2.2. Condition including the effect of bending

In some cases (especially when glued joints are thick), bending moments could appear. According to classical theory presented in the preceding paragraph, deformations perpendicular to glued joint cannot be taken into account. The assumption adopted that pressure perpendicular to the joint equals zero (or nearly so), can be allowed everywhere except the area near the end of element. In these areas appreciable normal stress values can be encountered. In the analysis taking into account bending, the glued joint in theoretical model is treated as a beam. It is also assumed that longitudinal forces P_k and P_c are not acting at element axes, but at their extreme fibres at the contacting surfaces (Fig. 2). Apart from this, all assumptions of par. 2.1 (except the last) remain valid.

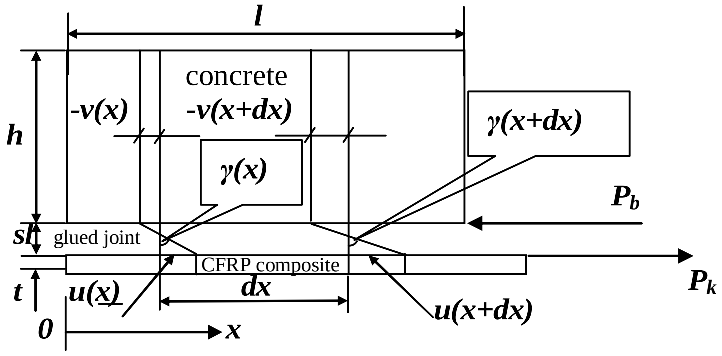

Fig. 2. Theoretical model taking bending effect into consideration

Normal stresses in concrete beam and glued element can be written in following form :

$$s_k(x) = \frac{P_k(x)}{tb_k} + \frac{P_k(x)t}{2W_k}, \tag{5}$$

$$s_c(x) = \frac{P_c(x)}{hb_c} + \frac{P_c(x)h}{2W_c}, \tag{6}$$

where b_c – width of concrete; b_k – width of the glued element (composite)

Taking into account section moduli in bending we obtain :

$$W_k = \frac{b_k t^2}{6} \Rightarrow s_k(x) = \left(\frac{P_k(x)}{tb_k} + \frac{3P_k(x)t}{t^2 b_k} \right) = \frac{4P_k(x)}{tb_k} \tag{7}$$

and:

$$W_c = \frac{b_c h^2}{6} \Rightarrow s_c(x) = \left(\frac{P_c(x)}{hb_c} + \frac{3P_c(x)h}{h^2 b_c} \right) = \frac{4P_c(x)}{hb_c} \ . \tag{8}$$

Can be written now in the form :

$$\frac{dt(x)}{dx} = \frac{G}{s}\left(\frac{4P_k(x)}{E_k t} + \frac{4P_c(x)}{E_c h} \right). \tag{9}$$

Since $P_k = P_c$, equation (9) can be presented in the form :

$$\frac{dt(x)}{dx} = \frac{G}{s}\left(\frac{4}{E_k t} + \frac{4}{E_c h} \right) P_k(x). \tag{10}$$

Differentiating with respect to x, we obtain :

$$\frac{d^2 t(x)}{dx^2} = \frac{G}{s}\left(\frac{4}{E_k t} + \frac{4}{E_c h} \right) \frac{dP_k(x)}{dx} \ . \tag{11}$$

In view of

$$t(x) = \frac{dP_k(x)}{dx} \tag{12}$$

and

$$l^2 = \frac{4G}{s}\left(\frac{1}{E_k t} + \frac{1}{E_c h} \right), \tag{13}$$

equation (11) can be written as a second order differential equation :

$$\frac{d^2 t(x)}{dx^2} - l^2 t(x) = 0 \, . \tag{14}$$

Applying the same reasoning as in previous paragraph we can write :

$$t(x) = l \ P_k(l) \frac{\cosh(lx)}{\sinh(ll)}, \tag{15}$$

where, according to (13) :

$$l = \left[\frac{4G}{s}\left(\frac{1}{E_k t} + \frac{1}{E_c h}\right)\right]^{1/2}. \qquad (16)$$

If we assume that shear stress distribution over the width b_k is constant, we can write:

$$t(x) = l \; \frac{P_k(l)\cosh(l\,x)}{b_k \sinh(l\,l)}. \qquad (17)$$

Graphical form of Eq. (17) is shown in Fig. 3, assuming the origin of the co-ordinate system :
a)in the middle of the reinforced element length (symmetrical tensioning of the glued strip) and
b) at the end – asymmetric (the glued strip is tensioned from one end only)

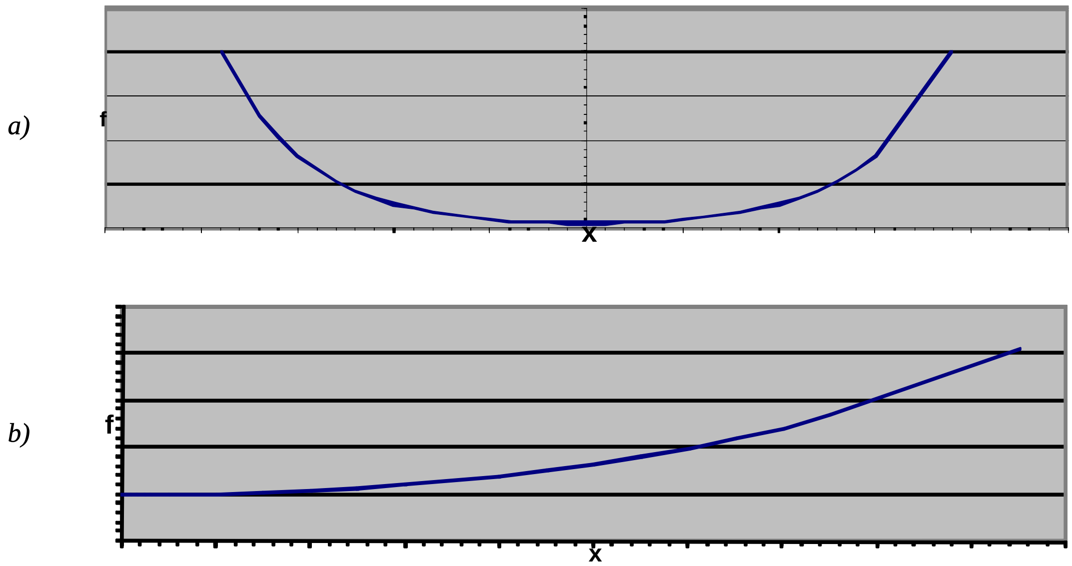

Fig.3. Graphs of the function $f = t(x) = l \; \frac{P_k(l)\cosh(l\,x)}{b_k \sinh(l\,l)}$ *with forces acting :*

a) at both ends and b) at one end of the glued composite

In order to determine the practical influence of taking bending effect (i.e. the deformations perpendicular to the joint) into consideration, calculations have been carried out of shear stresses present in the glued joint of the investigated beam. Calculations have been made for two joint thicknesses, i.e. *for s = 1mm and s = 2mm*. Extreme values of stresses are shown in Table.

Comparison of extreme values τ in glued joint

Joint thickness	Bending not considered		Bending effect considered		τ_{max1}/τ_{max2}	τ_{min1}/τ_{min2}
	τ_{max1}	τ_{min1}	τ_{max2}	τ_{min2}		
[mm]	[MPa]	[MPa]	[MPa]	[MPa]	[%]	[%]
1	20,597	4,923	20,009	0,588	102,9	837,0
2	22,135	9,486	20,103	2,032	110,1	466,8

From the above calculations follows that the influence of bending effect is important, particularly in case of minimum values. This influence depends, of course, on many factors, on joint thickness, glued strip thickness, stiffness ratio between the strengthened and the glued elements and joint length. The presented calculations also show, that the thinner glued joint, the lower the values of shear stresses.

3. Description of the stressing system. Taking into account experience gained abroad during early applications of the stressed strip, as well as the conditions prevailing in the country and theoretical discussion presented above, an attempt was made to strengthen a prestressed concrete girder by means of stressed composite strip. The strengthening system is proposed as universal, fitting the strengthened structures of different materials and various shapes. Various possibilities of introducing prestressing force have been also taken into consideration [18].

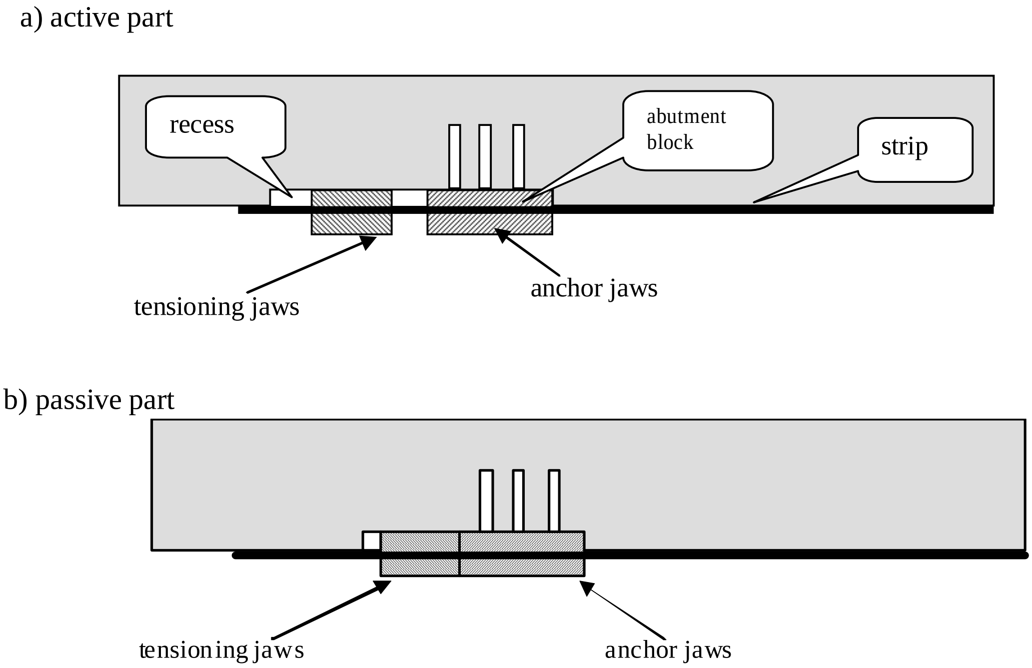

Fig. 4. Schematic drawing of strip stressing system

The composite strip stressing system presented here is taking advantage of foreign experience, but differs from the remaining systems in that arbitrary devices can be used for tensioning the strip, such as typical pulling devices, hydraulic servo-motors, presses, hoists or hydraulic cylinders. It was assumed that depending on the device used, the jaws at the active end can be of pulling or pushing type. The principle of strip tensioning is schematically shown in Fig. 4.

Apart from the elements schematically shown in Fig. 4., an abutment block is needed for the device tensioning the strip. This abutment block can be situated in front or behind the tensioning jaws. If – for instance – pulling device shall be used, the block shall be placed behind the jaws, when servo motor shall be used – the block shall be placed in front of them.

The solution of all difficulties connected with technical conditions of composite strip tensioning system is not an easy task. Very low strength in the direction perpendicular to fibres and negligible strength in transferring bending moments in any plane, are characteristic of carbon fibre reinforced strip. In addition, friction coefficients between the strip and other durable structural materials have negligible values. Significant difficulties are therefore present in solving the problems connected with anchorages.

It was assumed that in the anchorage zone of each strip a recess shall be made, necessary for placing the abutment block and allowing the tensioning jaws to be positioned at suitable level and place. Abutment block is placed first in the recess, anchored in the strengthened structure in such a way as to form one plane with the surface of the strengthened structure (the plane to which the strip is glued). When the tensioning and anchoring process of the strip is finished, the tensioning jaws are dismantled at both ends (active and passive) and strip ends glued to construction after filling the recesses with adhesive. For the trial application of stressed strip to the investigated girder, two strips 50mm wide were used. The entire tensioning and anchorage systems have been designed for these strips only.

A serious obstacle to overcome is the tensioning of composite strip in such a way as to avoid stress concentrations that could cause the destruction of the strip. From theoretical analysis follows that at the ends of the tensioned (i.e. stressed) strip appreciable stress concentrations occur. They are proportional to the value of the force stretching the strip. Stressing the strip in one cycle up to the full stressing force required to strengthen the structure creates the danger of its destruction because of stress concentrations at its ends.

The stresses in the normal plane should be checked every time, and this is – in addition – complicating the problem. To lower stress concentration at strip ends, it was decided to carry out stressing in several stages, with anchorage using short jaws. The strip shall be sequentially stressed so that the stress level is diminished several times. In practice, four short jaws were used and the strip was stressed in four stages. In stressing jaws, the external clamping plates differ from the plates in anchorage jaws : they are four times narrower and pressed down by one pair of high tensile bolts only.

Uniform stress distribution due to pressing down is assured by suitable construction of tensioning jaws. They consist of two steel plates, pressure blocks and stressing bolts with nuts (Fig. 5).

Fig. 5. Prestresing jaws

When the strip is stressed and anchored in abutment block by means of anchoring jaws, the stressing jaws can be dismantled and taken away. The dismantling of the jaws must be carried out in strict sequence to diminish equally and gradually the pressure on the strip. Stressing jaws elements can be used repeatedly.

The technology of strengthening using stressed CFRP strip is in principle not complicated, but requires a precise, almost perfect quality of execution. In particular, blocking in stressing and anchoring jaws and also the release of temporary, stressing jaws is a very sensitive operation decisive to the success or failure of the project.

Program and aim of investigations. The investigations were carried out at the Road and Bridge Research Laboratory in two parts. The first, initial part concerned the tests on efficiency of CFRP strip anchorage in steel jaws. These tests were necessary for verification and improvement of the design of composite stressing system. The second, proper part, concerned the assessment of prestressing system and effectiveness of strengthening of the trial girder. The program of the second part included the following stages:

- determination of girder stiffness and fissuring moment without strengthening; stage 1
- determination of strengthened girder stiffness; stage 2,
- investigation of the strengthened girder behaviour under cyclic loading (dynamic investigations); stage 3,
- determination of the cracking moment of the strengthened girder; stage 4,
- determination of the form of failure of the strengthened girder; stage 5.

5. Description of the test girder. Test girder adopted for investigation was a typical prestressed switch sleeper of length l_c = 490 cm and trapezoid cross-section of dimensions : depth h_c = 22 cm, bottom width b_d = 29 cm and top width b_g = 26 cm. Prestressing steel consisting of 12 Ø 7 mm dia wires is symmetrically placed in the cross-section. The beam is cast of B50 concrete and shear reinforcement consists of 7 mm dia. stirrups of ST3SX steel spaced at 15 cm.

The strengthening consisted of two CFRP strips (total width = 75 mm) prestressed to 112.5 kN. The longitudinal elasticity modulus of the strip was E_L = 210 kN/mm^2. The prestressing activities were carried out in the following order:

- preparation of base – exactly as in the classical case of strengthening using composite strip, such as repairs, forming etc.,
- assembling of anchoring element in the strengthened structure,
- fitting CFRP) strip,
- installation of stressing appliance,
- stressing the strip,
- anchoring the stressed strip,
- removing the stressing appliance,
- gluing the unstressed strip ends and protecting the strip with adhesive.

General view of the strengthened girder its shown in Fig. 6.

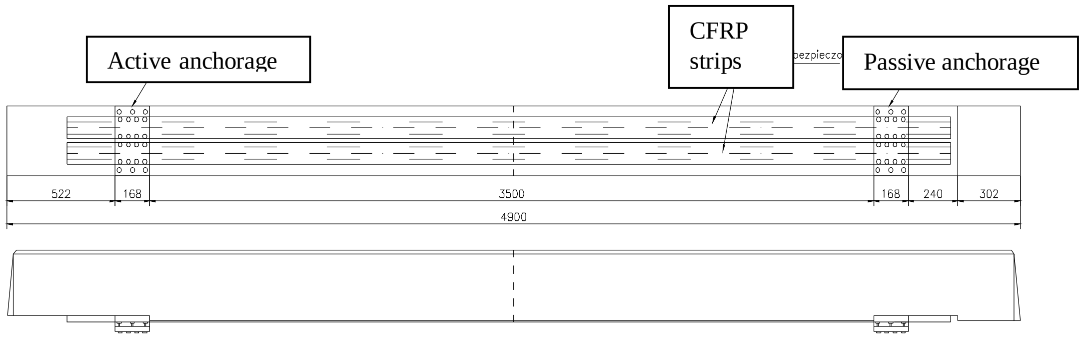

Fig. 6. Girder strengthened by stressed CFRP strips

6. Methodology and selected investigation results. Test girder was subjected to static and dynamic loading by a concentrated force acting vertically at mid-span. Even if this loading scheme does not produce the zone of pure bending, it was accepted as it allows to produce greater value of bending moment and also it is nearer to the scheme occurring in reality. The deflections were measured by induction gauges of 0.01 mm accuracy and unit strains by electric resistance strain gauges of reference base 50 mm and 10 mm. Schematic drawing of beam loading and positions of measuring gauges is shown in Fig. 7. Following measuring instruments were used:

- Huggenberger dial gauge of 0 – 50 mm range and elementary graduation 0.01mm;
- induction gauge HBM WA/100mm –T, of 0-100mm range, measuring capacity 0.01 mm with HBM SPIDER 8 bridges and a computer with Catman V2.0 program;

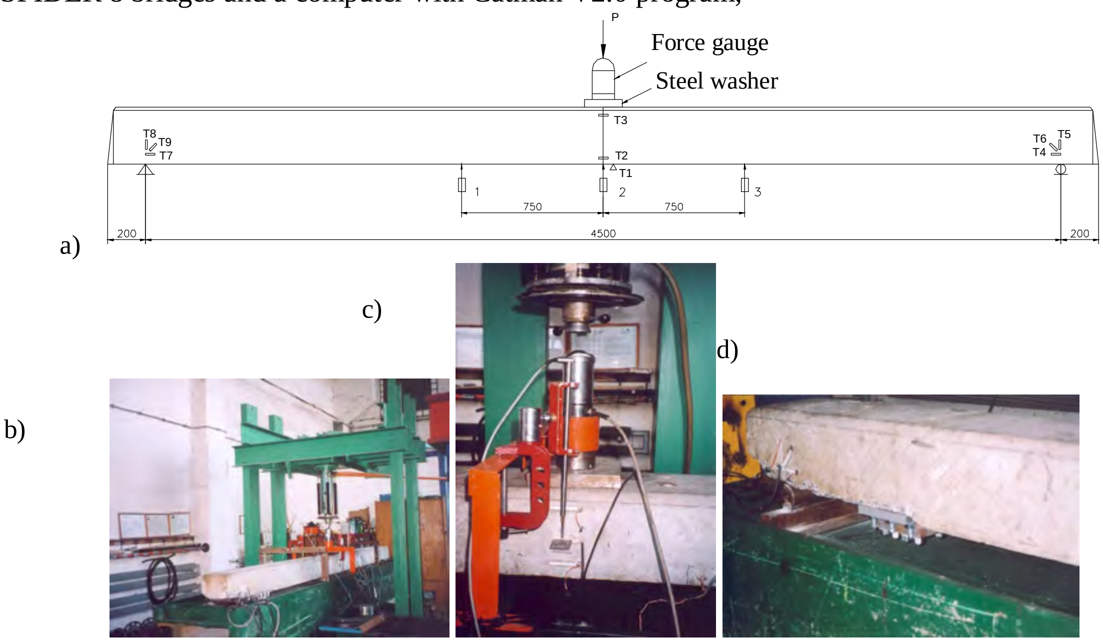

Fig. 7. Girder testing and situation of measuring points a) schematic drawing, b) overall view during investigations, c) view at mid-span, d) view near support

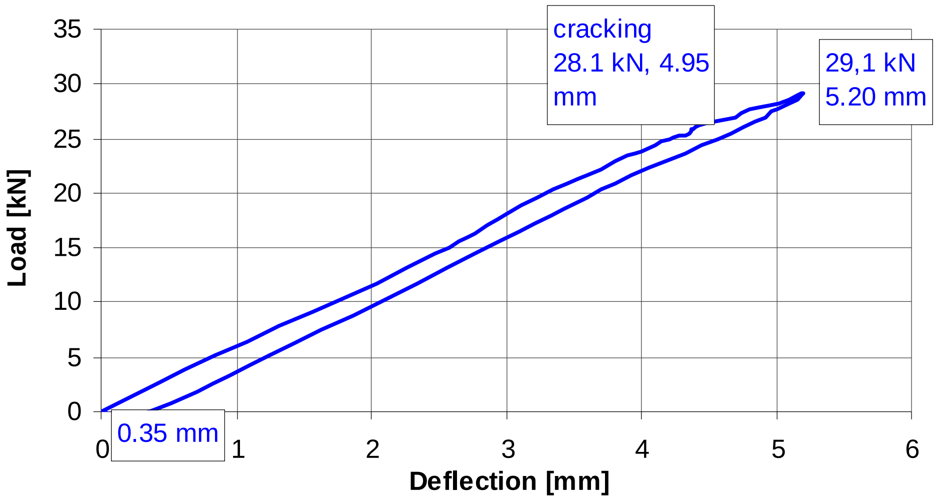

Fig. 8. Deflections at mid-span of beam (not strengthened). Stage 1

- Strain gauge FT-5107/100 kN;
- electric resistance strain gauges TFs – 350/10;
- electric resistance strain gauges RL 300/50.

The load during the tests was controlled by force gauge. The graph of deflections with relation to force in the first stage of investigations is shown in Fig. 8.

During the 1st stage of investigations it was found that cracking of the beam occurred at the load P_r = 28.1 kN, what corresponds to cracking moment M_r = 31.61 kNm. Total deflection at mid-span at cracking moment amounted to y_r = 4.95 mm and durable remaining deflection y_{tr} = 0.35 mm.

In the 2nd stage (i.e. after strengthening) the girder was subjected to the load 25% higher than the cracking load on not strengthened girder. At load P_r = 28.1 kN the obtained deflection was y_r^w = 3.90 mm. The deflection of the strengthened girder (Fig. 9) is about 27% smaller than the deflection in case of not strengthened girder at the same level of loading.

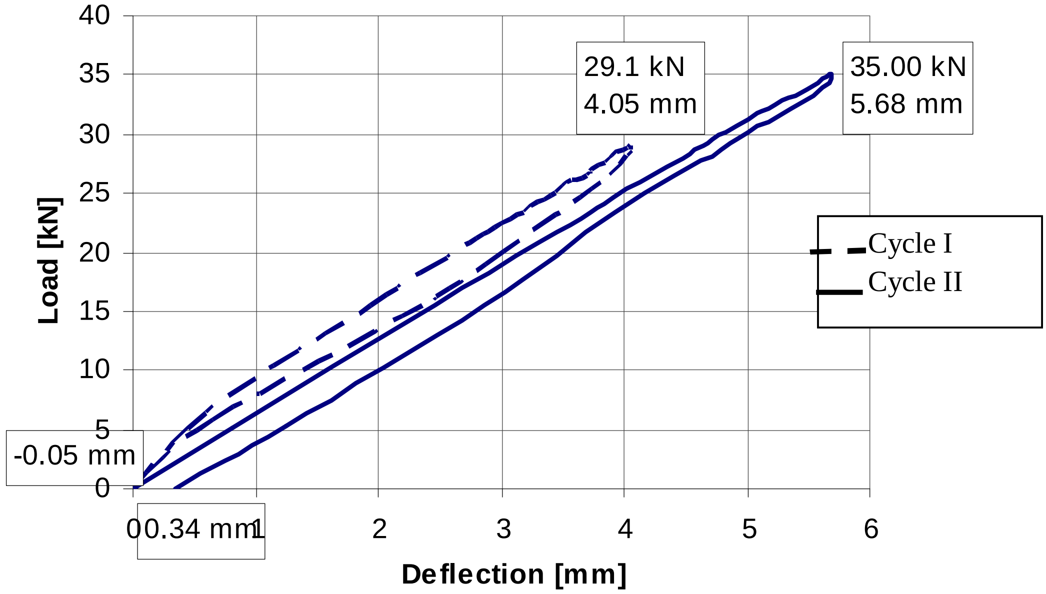

Fig. 9. The graph of mid-span deflections of girder in 2nd stage of investigation

The remaining permanent part of deflection is also much smaller ; in fact – it is comprised within the measuring error. It is a proof of fully elastic character of girder behaviour. In Fig. 10. a) and b) are shown the curves of strains measured in CFRP strip, and in Fig.10. c) the strains in the girder.

In stage 3 of investigations the strengthened girder was subjected to cyclic loading of 5 Hz frequency and force amplitude defined by P_{min} = 5 kN and P_{max} = 30 kN. The tests were carried out to 2 * 10^6 load cycles. As the result of dynamic loading, neither any damage to the girder nor any changes in strip anchorage were observed.

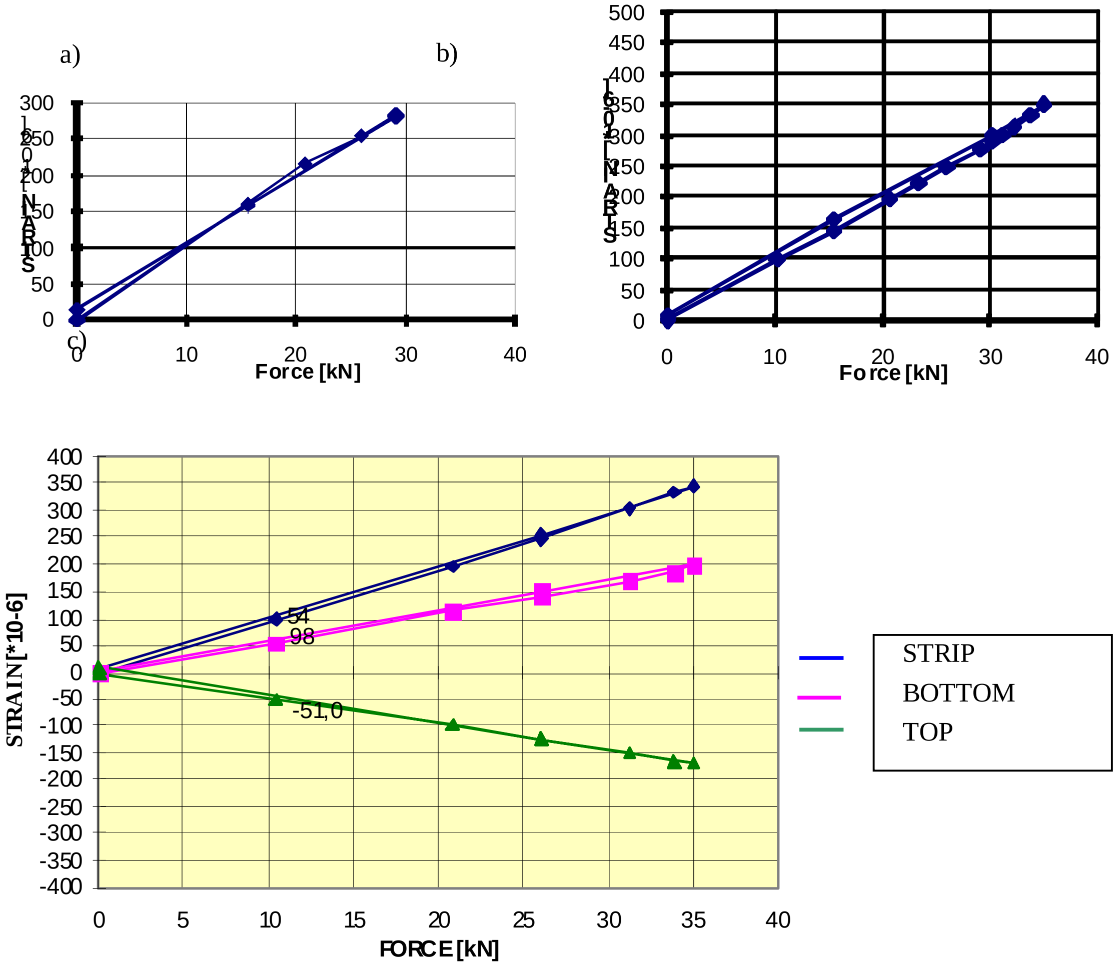

Fig. 10.a) Strains in CFRP strip measured during stage 2 cycle I of investigations, b) Strains in CFRP strip measured during investigations in stage 2, cycle II, c) Strains in the investigated girder, measured in stage 2

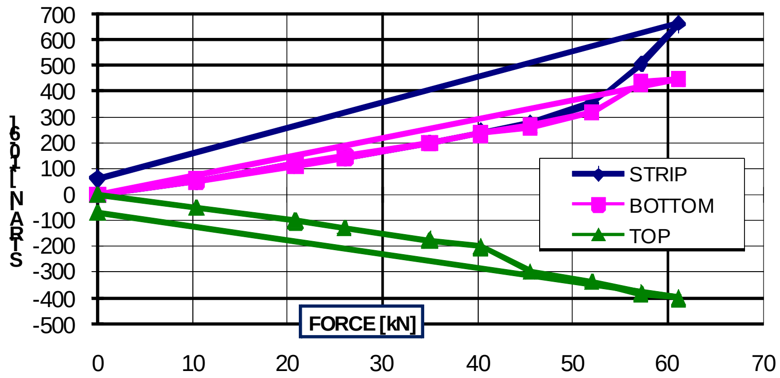

Fig. 11. Investigation of girder up to cracking of strengthened beam; deflections at mid-span, stage 4

After dynamic investigations, the girder was subjected to an increasing load up to attaining the cracking load (4th stage of investigation). First crack appeared at load P^{lw}_r = 45.5 kN but successive cracks were observed only at the loading P^w_r = 61.1 kN. The deflection y^{lw}_r = 7.65 mm corresponds to force P^{lw}_r

and – deflection $y^W{}_r$ = 10.85 mm – to force $P^W{}_r$. Start of cracking corresponds to cracking moment $M^W{}_r$ = 51.19 kNm (stage 4). It was found that it was greater by 62% than M_r = 31.61 kNm (stage 1 – not strengthened beam). It is remarkable that the permanent part of deflection remaining after the load cycle reaching P = 79.0 kN – was only $y^{wr}{}_{tr}$ = 0.70 mm. Strains measured in the investigated girder during its loading leading to fissure are shown in Fig. 11.

In order to determine the form of failure in stage 5 of investigations, the beam was loaded to failure level, amounting to P_n = 92.8 kN with deformation at mid-span y_n = 56.05 mm. The failure occurred by simultaneous rupture of strip, formation of many cracks at bottom of the beam and crushing of its top part at mid-span. The graphs of girder deflections in stages 4 and 5 are shown in Fig. 12; destruction zone in Fig. 13; and in Fig. 14 the strains registered on tape during loading to failure.

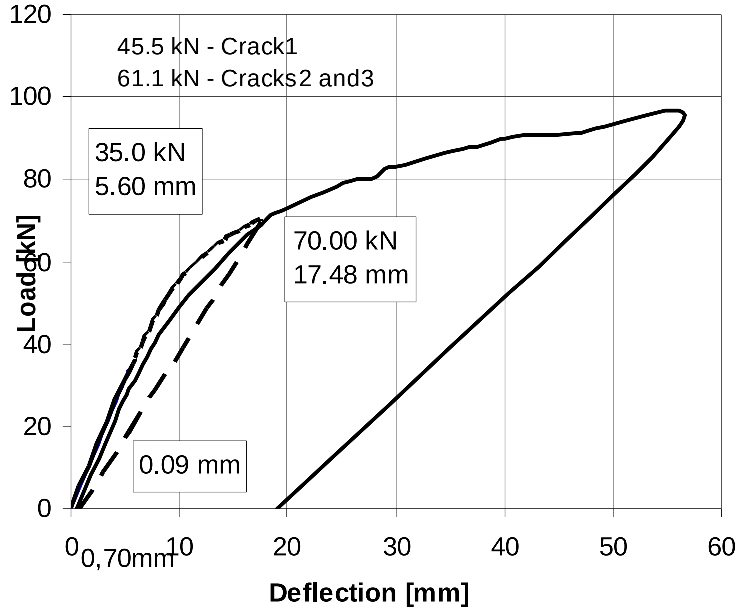

Fig. 12. Curves of deflection at girder mid-span during investigations, stages 4 and 5

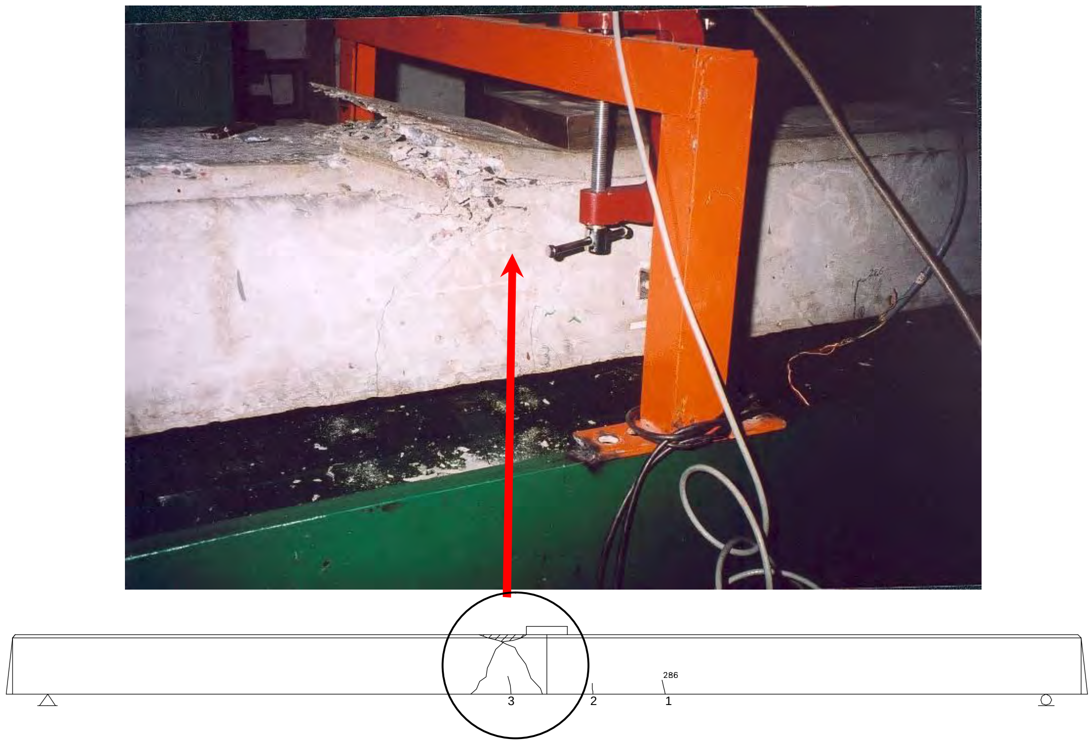

Fig. 13. Form of girder failure

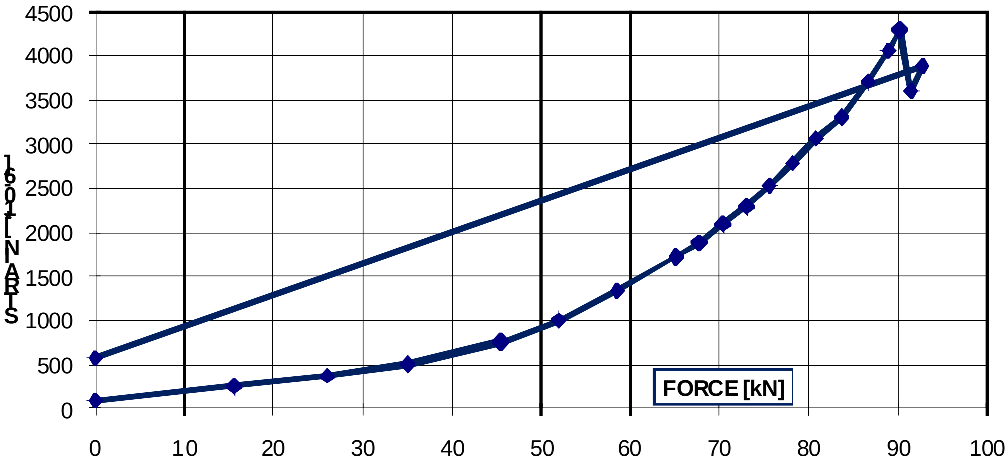

Fig. 14. Test of the strengthened girder to failure ; strains of CFRP strip at mid-span, stage 5

7. Conclusions. Beam strengthening by tensioned CFRP strip was carried out in Poland in 2003 for the first time. Investigations proved that very effective stressing of structures by tensioned composite strip is possible. The chosen calculation parameters and those gained in practice showing the effectiveness of strengthening are as follows: bending moment at cracking, unit strain in strip and deflections.

Stressed carbon fibre composite strips (CFRP) are included in transferring dead loads of the structure, reduce stresses in existing reinforcement and share in transferring live loading by the strengthened structure. The investigations presented above prove that the deflection of the strengthened girder is about 27% smaller than the deflection of the not strengthened girder at the same level of loading. It was found that the cracking moment was increased by 62% due to strengthening. The permanent residue of deflection is also decidedly smaller. This is a proof of fully elastic character of girder behaviour within the range of service loads. No damage whatsoever of the girder nor any changes in strip anchorage were observed. This proves that technology of stressing was suitably chosen and anchorage was well designed, making possible the transfer of real stresses, preventing their concentration. This allowed to strengthen the structure safely and effectively, taking full advantage of the strength properties of composite strip. This opens new possibilities of strengthening the existing structures.

After successful laboratories' tests, first application of own system onto full industrial scale was moved in Poland [19]. Strengthening it came under twenty of been reinforced concrete in Tychy and five girders of bridge in east Poland. Amplification of every girder was designed two tapes CFRP SikaCarboDur® S512 strained strength after 80 kN and glued to bottom of beams. To prestressing hydrhaulic jack LARZEP SM 01015 was used (fig. 15).

Fig. 15. Active anchorage

All connected works with prestressing of strips CFRP ran very skilfully and without disturbances. Work out by IBDiM system turned out industrial conditions very effective.

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