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RESEARCH ON FLEXURAL CALCULATION THEORY OF REINFORCED CONCRETE T-BEAM STRENGTHENED BY STEEL WIRE MESH AND POLYURETHANE CEMENT (SWM-PUC) COMPOSITE

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ABSTRACT

In order to solve the problem of poor bonding and easy peeling of reinforced concrete structure strengthened by steel wire mesh and polymer mortar (SWM-PM). In this paper, a steel wire mesh and polyurethane cement (SWM-PUC) composite strengthening technique is presented. The flexural properties of one unreinforced beam, two SWM-PM strengthened beams and four SWM-PUC composite strengthened beams were studied experimentally. The experimental results show that the SWM-PUC composite reinforcement layer can improve the load carrying capacity and rigidity of reinforced concrete beams and limit the unfolding cracks significantly. The SWM-PUC composite strengthened beams have pure bending damage and peeling damage between the strengthening layer and the concrete has not occurred. However, SWM-PM strengthened beams with the same SWM reinforcement ratio occurred with peeling damage between the reinforcement and the concrete. On basis of an experimental study, the theoretical formulas for cracking load, ultimate load, deflection and width of crack of SWM-PUC composite strengthened beams are proposed by the simplified stress-strain constitutive relation of the material and the theoretical formulas are deduced with the code. By contrasting the test results with the theoretical computation results, the accuracy of the experiment results and the reliability of the theoretical formulas were verified.

KEYWORDS

Steel Wire Mesh and Polyurethane (SWM-PUC) Cement Composite, Flexural Strengthening, Reinforced Concrete Beam, Calculation Theory

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INTRODUCTION

Bridges play a vital role in highway transportation and are indispensable infrastructure. However, with the passage of time and the influence of the natural environment, coupled with the overloading of vehicles and outdated design standards, concrete bridges are subject to problems such as material aging, cracking and insufficient bearing capacity [1-3]. From the economic and environmental point of view, adopting a reasonable method of maintenance and reinforcement can produce good economic and social benefits.

At present, the main reinforcement methods for reinforced concrete bridges [4-5] are pasting carbon fiber plates [6-7] and pasting steel plates [8]. Pasted steel plate reinforcement method and pasted carbon fiber plate reinforcement method are convenient in construction, both of which can greatly increase the bearing capacity of specimens and hardly affect the structural headroom height. However, the aging resistance of the carbon fiber plate material itself is poor, and the steel plate is prone to corrosion in the environment of nature. Because of the uneven surface of the concrete beam, the steel plate and carbon fiber plate are difficult to fit well with the concrete surface. There is an urgent need to solve the problem of durability after the strengthening of pasted carbon fiber plates and pasted steel plates.

Steel wire mesh (SWM) is used for bridge structural strengthening due to its good tensile strength, toughness and durability [9-11], often using cement-based such as polymer mortar [12-14] and engineered cementitious composite (ECC) as its bonding and anchoring material with concrete [15-16], polymer mortar and ECC have good film-forming properties, which can adapt to the uneven surfaces of the concrete structure being strengthened. Fang Y, through the experimental study on the flexural strength of beams reinforced with high-strength wire mesh and ECC composite materials, found that the SWM and engineered cementitious composite (SWM-ECC) strengthening layer can significantly increase the flexural resistance and stiffness of the reinforced beams, and decrease the width of the cracks in the composite layer and delay the development of the concrete cracks [17]. However, ECC is a cement-based material that requires wet work, which has problems with long curing time and low early strength. In addition, the poor bonding of ECC materials to the strengthened beams results in peeling damage to the SWM-ECC strengthening layer and the strengthened beams, which reduces the utilization rate of the SWM [18-19]. Xing G, conducted a flexural loading experimental study on steel wire mesh and polymer mortar (SWM-PM) strengthened RC beams, and SWM-PM was found to be effective in improving the load carrying capacity and rigidity of RC beams, but the tentative strength and bonding properties of polymer mortar material have certain limitations, and cracking of the SWM-PM reinforcement layer and stripping of the reinforcement layer from the concrete surface occur, affecting the durability of the reinforced bridge structure [20].

To solve the problem that the bonding between the strengthening layer and concrete of reinforced concrete T-beam strengthened by SWM is poor and easy to peel off, the strengthening efficiency of reinforced concrete T-beam strengthened by SWM is further improved. In this paper, a method of strengthening existing reinforced concrete beams by using steel wire mesh and polyurethane cement (SWM-PUC) composite materials is proposed. Through the flexural experiment of SWM-PUC composite strengthened reinforced concrete T-beams, the change law of flexural performance of strengthened beam is explored, and to clarify the crack development, damage mode and load carrying capacity of the SWM-PUC composite strengthened reinforced concrete T-beams are clarified. Based on the experimental study, the flexural calculation method of the strengthened reinforced concrete T-beam by SWM-PUC composite strengthening is proposed.

TEST PROFILE

Material Properties

Concrete

Ordinary silicate cement was used for cement, natural river sand was used for fine aggregate, and two kinds of graded crushed stone with diameters ranging from 5 to 25 mm and 25 to 31.5 mm were used for coarse aggregate. The 28-day cubic compressive strength and flexural strength of the concrete are measured to be 31.8 MPa and 5.30 MPa, respectively. The modulus of elasticity of the concrete was 30 GPa and Poisson's ratio was 0.2.

Steel

The diameter of the tensile reinforcement is 18 mm, and the diameter of the stirrups and erection reinforcement is 8 mm. The yield strengths of the 18 mm and 8 mm diameter reinforcement is 400 MPa and 335 MPa, respectively, and the ultimate strengths are 600 MPa and 510 MPa, respectively. The modulus of elasticity of the reinforcement is 200 GPa and Poisson's ratio is 0.3.

SWM

The type of steel wire is 6 x 7 + IWS (a steel wire has 6 strands, each consisting of 7 steel wires, with IWS as the center metal strand core). The steel wires mesh is made of steel wires with a diameter of 2.4 mm, the area of a single steel wire is 4.52 mm^2, the tensile strength is 1520 MPa, the elastic modulus is 140 GPa, and the ultimate tensile strain is 0.0187.

Polymer Mortar

Polymer mortar is made by mixing cement, fine aggregate, polymer emulsion and admixtures. Polymer emulsion is an important component of polymer mortar. The compressive and flexural strengths of the polymer mortar are measured to be 55 MPa and 5.6 MPa, respectively. The modulus of elasticity of polymer mortar is 23.1 GPa.

PUC Material

PUC material is polymerized from polyester polyols, isocyanates and cement. The combination PUC as presented in Table 1. The axial tensile test of the PUC material measured a tensile strength of 35.6 MPa. PUC has a tensile modulus of elasticity of 5500 MPa and an ultimate tensile strain of 7000 με. The expression of PUC obtained by fitting the result data is as follows:

$$\sigma_{\mathrm{PUC}} = -0.24566\varepsilon_{\mathrm{PUC}}^{2} + 6.85318\varepsilon_{\mathrm{PUC}} - 0.34356 \tag{1}$$

where σ_{PUC} is the stress of PUC material, ε_{PUC} is Strain of PUC material.

Tab. 1 - The mix ratio of PUC material

Components of PUC	Ratio/%
Polyester polyol	25
Isocyanate	25
Concrete	40
Molecular sieve	10

Specimens Design

A total of seven reinforced concrete (RC) beams were designed for the experiment, including one unreinforced beam, two SWM-PM reinforced beams, and four SWM-PUC composite strengthened beams. The beam length is 3800 mm, the upper flange width is 360 mm and the beam height is 320 mm. The thickness of the concrete protective layer is 25 mm. The distance of the loading point from the support is 1500 mm and the shear span ratio is 5.5.

The main parameters of the test were in addition to the type of bonding anchorage material in the reinforcement layer. The reinforcement ratio of the SWM, the thickness of the PUC, the anchoring method and the loading method were also considered. For a beam with initial damage, the beam is preloaded before strengthening so that the maximum crack width of the beam is 0.2 mm. After unloading, the beam is strengthened. After the strengthening and maintenance are completed, the graded loading is carried out. The specimen design parameters are presented in Table 2.

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Tab. 2 - Specimens design parameters

Beam	Bonded anchoring materials	Bonded anchoring materials thickness(mm)	Number of longitudinal steel wires	End anchoring method	Loading method
CB	-	-	-	-	-
B1	Polymer mortar	20	8	-	-
B2	Polymer mortar	20	8	End U-shaped anchorage	-
B3	PUC	20	5	-	-
B4	PUC	20	8	-	-
B5	PUC	30	5	-	-
B6	PUC	20	8	-	Preload

Loading and Measuring Programs

The loading method of the test was four-point bending loading, and the loading device as presented in Figure 1. There test beams were all simply supported beams with a 3600 mm span and a distance of 600 mm between the two loading points. Preload the test beam before official loading and inspect all the test instruments and meters to see if they work properly. Before cracking of the test beams, the loading level was 2 kN. The loading level after cracking of the test beams was 5 kN, and the loading was stopped when the maximum crack of the test beams exceeded 1 mm. Displacement gauges were arranged at the center of the beam span and at the loading point location to measure the deflection during the loading process. Concrete strain gauges were arranged along the beam height of the experimental beam to measure the concrete strain during the loading process. Strain gauges were placed in the tension reinforcement to measure the reinforcement strain. Strain gauges were arranged at the strand position in the middle of the span to measure the strain of the strand during loading. All measurements were collected by a static strain collection box.

Fig. 1 - Test loading device diagram

TEST RESULTS AND ANALYSIS

Cracking Load

The cracking loads of all the specimens are presented in Table 3. The cracking load of beam CB was 10 kN. The cracking load of beam B1 reinforced with SWM-PUC was 14 kN, which was a 40% increase over beam CB. The cracking load of beam B2 reinforced with SWM-PM was 16 kN, which was a 60% increase over beam CB. Due to the U-shaped anchorage of beam B2, the cracking load of beam B2 was elevated by 2kN compared to beam B1. Beam B3 was strengthened with a SWM-PUC composite with a cracking load of 18 kN. Beam B4 had a cracking load of 20 kN. With the same thickness of the strengthening layer, the reinforcement ratio of the SWM in the strengthening layer of beam B4 was larger than that of beam B3, so the cracking load of beam B4 was elevated by 2 kN compared with that of beam B3. The cracking load of beam B5 was 22 kN, and the thickness of the strengthening layer of beam B5 was larger than that of beam B3 with the same configuration of the strengthening layer's SWM, and the cracking load of beam B5 was elevated by 4kN compared with that of beam B3.

Tab. 3 - Characteristic load test value

Beam	Cracking load/kN	Increase relative to CB/%	Yield load/kN	Increase relative to CB/%	Ultimate load/kN	Increase relative to CB/%
CB	10	-	60	-	80	-
B1	14	40	70	16.6	85	6.3
B2	16	60	75	25	94	17.5
B3	18	80	79	31.6	112.8	41
B4	20	100	85.8	43	122.6	53.3
B5	22	120	98	63.3	140	75
B6	-	-	84	40	120	50

Yield Load and Ultimate Load

(1) Yield load

The yield loads for all specimens are shown in Table 3. The yield load of beam CB was 60 kN. The yield loads of beams B1 and B2 were 70 kN and 75 kN, respectively, and the yield loads were elevated by 16.6% and 25%, respectively, compared with beam CB. Showing that the SWM-PM reinforcement method can enhance the yield load of the strengthened beams. Beam B2 was anchored with U-shaped anchor, beam B2 had a 5 kN higher yield load than beam B1. The thickness of the strengthening layer of beam B1 and beam B4 was the same as the reinforcement ratio of the SWM in the strengthening layer, and the yield load was 70 kN and 85.8 kN, respectively. The yield load of beam B4 was 22.6% higher than that of beam B1. It indicates that the SWM-PUC composite can better enhance the yield load of strengthened beams. The thickness of the strengthening layer was the same for beam B3 and beam B4, and the yield loads were 79 kN and 85.6 kN, respectively. The yield load of beam B4 was elevated by 8.6% compared to beam B3. The reinforcement ratio of the SWM in the strengthening layer of beam B3 and beam B5 was the same, and the yield load was 79 kN and 98 kN, respectively. The yield load of beam B5 was elevated by 24.1% compared to beam B3. Beam B6 was a preloaded beam. The ultimate loads of beam B6 and beam B4 were 43 kN and 40 kN, respectively. It shows that SWM-PUC strengthening had a good strengthening effect on beams with initial damage.

(2) Ultimate load

The ultimate loads of the specimens are shown in Table 3. The thickness of the strengthening layer of beam B1 and beam B4 was the same as the reinforcement ratio of the SWM in the strengthening layer. The ultimate loads were 86 kN and 122.6 kN, respectively, and the difference in ultimate load was 36.6 kN. The thickness of the strengthening layer was the same for beam B3 and beam B4. The ultimate load of beam B4 was elevated by 8.7% compared to beam B3. The reinforcement ratio of the SWM in the strengthening layer of beam B3 and beam B5 was the same, and the ultimate load was 112.8 kN and 140 kN, respectively. The ultimate load of beam B5 was elevated by 24.1% compared to beam B3. The thickness of the strengthening layer of beam B4 and beam B6 was the same as the reinforcement ratio of the SWM in the strengthening layer. The ultimate load increase of the preloaded beam B6 was 50%. The ultimate load increase of beam B4 without preloading is 53.3%. The increase in the ultimate load of both was almost the same.

Load-Strain Curve Analysis

Longitudinal Reinforcement Strain

It can be seen from Figure 2 that the longitudinal reinforcement strain is linearly related to the load before cracking of the specimen. When the load reached 40 kN. The strain in the unreinforced beam was 1585 με. The strains of beams B1 and B2 strengthened with SWM-PM were 1,288 με and 1,127 με. At this time, the strains of B3, B4, B5 and beam B6 strengthened by SWM-PUC composite were 853 με, 697 με, 632 με and 750 με, respectively. Under the same load, the strain change of the SWM-PUC composite strengthening specimen was small. The reason is that the SWM shares part of the load during the loading process so that the load increment of the strengthened beam is smaller for the same longitudinal reinforcement strain. With the increase in load, the reinforcement yielded and the constraint of the concrete by the SWM became more obvious. The load continued to increase and the SWM-PM strengthening layer peeled away from the concrete. However, the PUC remained well bonded to the concrete, and the slope of its load-reinforcement strain curve decreased slowly.

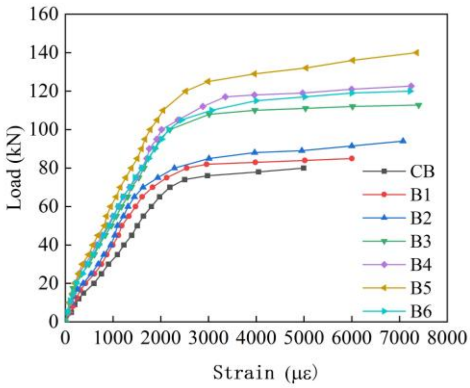


Fig. 2 - Load-reinforcement strain curve

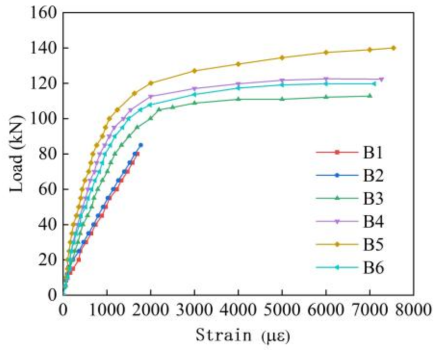


Fig. 3 - Load- steel wire strain curve

Longitudinal Reinforcement Strain

The load-steel wire strain curve as presented in Figure 3. The SWM is involved in the force throughout the loading process, and the load is linearly related to the strain in the steel wire before the beam cracks. With the increase of load, the cracks develop and expand gradually, the neutralization axis moves upward, and the strain in the SWM increases. When the steel wire yields, the strain of the SWM increases rapidly. This is because the stress of the steel wire remains constant and the load is shared between the SWM and the PUC until the composite reinforcement breaks. Among them, the SWM-PM strengthened beams B1 and B2, the strength of the SWM was not fully utilized because the strengthening layer was damaged by peeling off from the concrete, and the SWM was not pulled off.

PUC Strain

The load- PUC strain curves for beams B3, B4, B5 and B6 are shown in Figure 4. Under the same load, the strain of PUC of beam B5 was less than that of PUC of beam B3. It shows that the stiffness of the test beam increases as the thickness of polyurethane increases. Among them, the load-PUC strain curves of test beams B4 and B6 almost overlapped, indicating that they had the same stiffness. Furthermore, it showed that the beam still had good stiffness after being reinforced with cracks after preloading. The ultimate bearing capacity was the same as that of the test beam which had not been preloaded. The ultimate damage loads of the test beams for the four different working conditions were 112.8 kN, 122.6 kN, 140 kN, and 120 kN, respectively. At that time, the corresponding PUC strains were 7000 με, 7140 με, 7336 με, and 7071 με, respectively. Compared with polymer mortar materials, PUC materials had better bonding properties and tensile strength and had a better effect on bearing capacity when combined with steel wire strengthening.

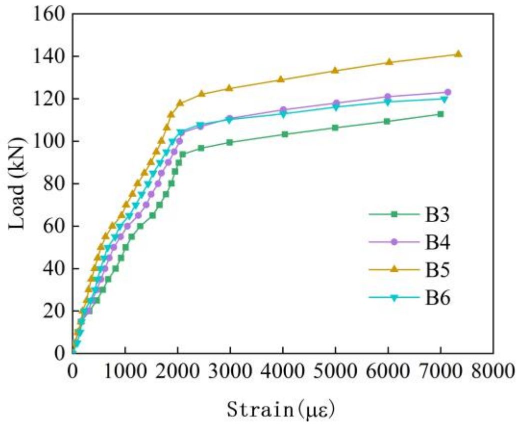


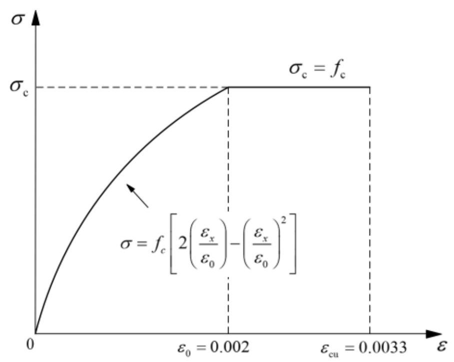
Fig. 4 - Load- PUC strain curve

DERIVATION OF THEORETICAL FORMULAS OF SWM-PUC COMPOSITE STRENGTHENED REINFORCED CONCRETE BEAMS.

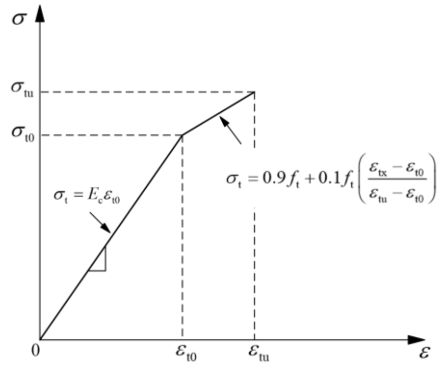
Basic Assumptions

The following fundamental assumptions are made for the computation of the bending capacity of the reinforced concrete T-beam in its normal section during bending after strengthening:

1. Neglect the bond-slip of the SWM-PUC composite strengthening layer in the contact area with the concrete.
2. Equivalent stress plot is used for concrete instead of actual curve stress plot. The height is the height of the compression zone and the width is the design value of concrete strength.
3. Before a flexural member reaches the limit state of load bearing capacity, the section strains are essentially consistent with the flat section assumption.
4. The constitutive relationship of concrete refers to the design code standard for concrete structures [26], as shown in Figure 5. After the concrete cracks, the tensile effect of the concrete is ignored.



(a) Compressive constitutive model



(b) Tensile constitutive model

Fig. 5 - Constitutive relation model of concrete

5. The three-stage stress-strain constitutive relationship model is used for the reinforcement. The elastic phase, yielding phase, and strengthening phase, in that order, are presented in Figure 6.

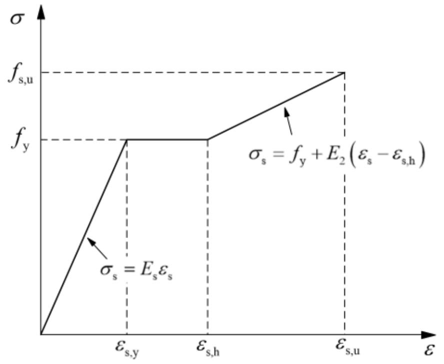


Fig. 6 - Constitutive relation model of reinforcement

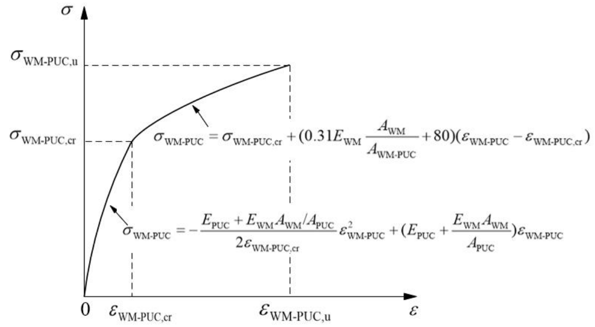


Fig. 7 - Constitutive relation model of SWM-PUC composites

6. The stress-strain constitutive relationship model of the SWM-PUC composite layer as presented in Figure 7. The model is divided into two segments, a rising segment and a strengthening segment for the elastic-plastic change of the PUC material. The calculation formula is as follows:

$$\sigma_{WM-PUC} = \begin{cases} \alpha\varepsilon_{WM-PUC}^2 + \beta\varepsilon_{WM\text{-}PUC} & \left(0 \le \varepsilon_{WM-PUC} \le \varepsilon_{WM-PUC,cr}\right) \\ \gamma\left(\varepsilon_{WM-PUC} - \varepsilon_{WM-PUC,cr}\right) + \sigma_{WM-PUC,cr} & \left(\varepsilon_{WM-PUC,cr} \le \varepsilon_{WM-PUC} \le \varepsilon_{WM-PUC,u}\right) \end{cases} \quad (2)$$

$$\begin{cases} \alpha = -\dfrac{E_{PUC} + \dfrac{E_{WM}A_{WM}}{A_{PUC}}}{2\varepsilon_{WM\text{-}PUC,cr}} \\ \beta = E_{PUC} + E_{WM}A_{WM} / A_{PUC} \\ \gamma = 0.31E_{WM}A_{WM} / A_{WM\text{-}PUC} + 80 \end{cases} \quad (3)$$

Bearing Capacity Analysis

Cracking Load

The structural mechanics method was used to analyze the internal forces of the strengthened beams under load. The stress relations for the strengthened T-beam are presented in Figure 8.

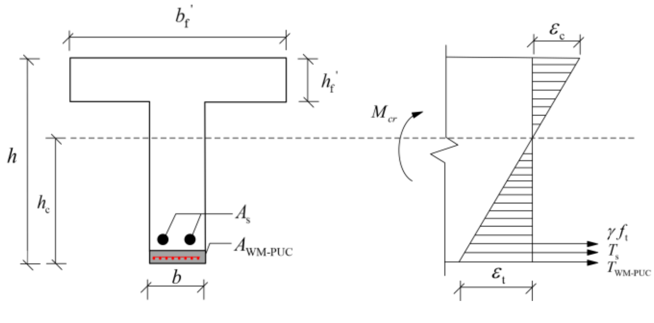


Fig. 8 - Cracking moment stress diagram

The split load of SWM-PUC reinforced RC-T beams can be computed according to the following equation:

$$M_{cr} = \gamma f_t W_0 \quad (4)$$

where γ is the coefficient of influence of plasticity of concrete under load, f_t is the concrete axial tensile strength, W_0 is the elastic resistance moment of the tension edge should be obtained by conversion. The conversion formula is as follows (5) ~ (9).

T-section beams with members in the elastic phase before cracking, the converted cross-sectional area A_0 is computed by the equation below:

$$A_0 = b_f^{'} h_f^{'} + b\left(h - h_f^{'}\right) + \left(n_s - 1\right) A_s + \left(n_{WM\text{-}PUC} - 1\right) A_{WM\text{-}PUC} \tag{5}$$

The static moment S_0 of the T-beam section is:

$$S_0 = b_f^{'} h_f^{'} \left(h - \frac{h_f^{'}}{2}\right) + b\left(h - h_f^{'}\right)\left(\frac{h - h_f^{'}}{2}\right) \tag{6}$$

The neutral axis h_c of the T-beam is:

$$h_c = \frac{S_0}{A_0} = \frac{b_f^{'} h_f^{'} \left(h - \frac{h_f^{'}}{2}\right) + b\left(h - h_f^{'}\right)\left(\frac{h - h_f^{'}}{2}\right)}{b_f^{'} h_f^{'} + b\left(h - h_f^{'}\right) + \left(n_s - 1\right) A_s + \left(n_{WM\text{-}PUC} - 1\right) A_{WM\text{-}PUC}} \tag{7}$$

Through the parallel shift formula, the moment of inertia I_0 of the converted section is obtained as:

Using the parallel shift equation, the expression for the moment of inertia1 of the converted section is derived as.

$$I_0 = \frac{b_f^{'}\left(h_f^{'}\right)^3}{12} + b_f^{'} h_f^{'} \left(h - h_c - \frac{h_f^{'}}{2}\right) + \left(n_s - 1\right) A_s \left(h_c - a_s^{'}\right)^2 + \left(n_{WM\text{-}PUC} - 1\right) A_{WM\text{-}PUC} \left(h_c - a_{WM\text{-}PUC}^{'}\right)^2 \tag{8}$$

Therefore, the resilient moment of resistance W_0 at the tension margin is:

$$W_0 = \frac{I_0}{h_c} \tag{8}$$

where n_s is the ratio of elastic modulus of steel bar to concrete, $n_s = \frac{E_s}{E_c}$, $n_{WM\text{-}PUC}$ is the ratio of modulus of resilience of SWM-PUC composite to concrete, $n_{WM\text{-}PUC} = \frac{E_{WM\text{-}PUC}}{E_c}$, $b_f^{'}$、 $h_f^{'}$ is the upper flange width, flange thickness, h、h_c is the reinforcement T-beam full section height, neutral axis section height, A_s、 $A_{WM\text{-}PUC}$ is the section area of the steel wire, SWM-PUC composite materials, $a_s^{'}$、$a_{WM\text{-}PUC}^{'}$ is the district from the point of steel wire ensemble to the margin of the tensile area, SWM-PUC ensemble to the margin of the tension area, S_0 is the static moment of T-beam section after reinforcement, h_c is the neutral axis of T-beam after reinforcement, W_0 is the elastic resistance moments of the strengthened T-beam.

The theoretical formula for the cracking load is:

$$F_{cr} = 0.75 M_{cr} \tag{9}$$

The computed and experimental values of splitting loads are presented in Table 4. As presented in Table 4, the cracking loads of T-beams strengthened by SWM-PUC composite showed significant improvement. And the reinforcement layer SWM reinforcement ratio and reinforcement layer PUC thickness the greater the influence. The computed values are in general accord with the experimental values.

Tab. 4 - Comparison of calculated and test values of cracking loads

Beam	CB	B3	B4	B5
Test value/kN	10	18	20	22
Calculated value/kN	9.5	16.5	18.6	20.5
Error value	5%	8.3%	7%	6.8%

Ultimate Load

The bearing capacity of beam CB was 80 kN. The bearing capacity of beam B3 with five longitudinal steel wires was 112.8 kN. The bearing capacity of beam B4 with eight longitudinal steel wires was 122.6 kN. Compared to the unstrengthen beam CB, the load carrying capacity of beams B3 and B4 increased by 41% and 53.3%, respectively. The bearing capacity of beam B5 with five longitudinal steel wires and 30 mm thickness of PUC was 140 kN. It was 75% higher than the unreinforced beam and 22% higher than beam B3 with the same reinforcement ratio. Based on the height of the pressure zone of the equivalent rigid stress map, the flexural components strengthened with SWM-PUC composite were divided into two types. The first type of flexural capacity calculation as presented in Figure 9.

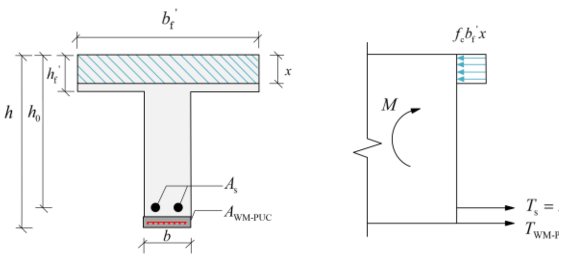


Fig.9 - The first type of flexural load capacity calculation diagram

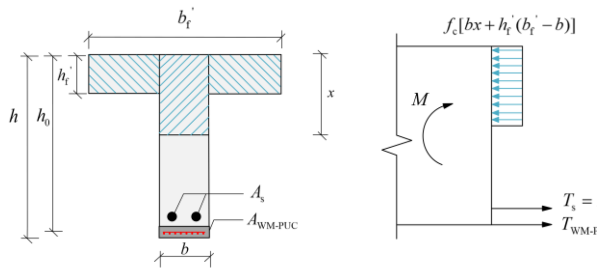


Fig. 10 - The second type of flexural load capacity calculation diagram

If the following equation is met, it is the first type of reinforced T-beam:

$$f_s A_s + \sigma_{\text{WM-PUC}} A_{\text{WM-PUC}} \leq f_c b_f^{'} h_f^{'} + f_s^{'} A_s^{'} \tag{10}$$

Find the height of the pressure zone according to this formula:

$$f_s A_s + \sigma_{\text{WM-PUC}} A_{\text{WM-PUC}} \leq f_c b_f^{'} x + f_s^{'} A_s^{'} \tag{11}$$

The bending capacity of the normal section is computed according to the following formula:

$$\gamma_0 M \leq f_c b_f^{'} x \left(h_0 - \frac{x}{2} \right) + f_s^{'} A_s^{'} \left(h_0 - a_s^{'} \right) \tag{12}$$

The second type of flexural capacity calculation is shown in Figure 10.

If the following equation is not met, it is the second type of reinforced T-beam:

$$f_s A_s + \sigma_{\text{WM-PUC}} A_{\text{WM-PUC}} \leq f_c b_f^{'} h_f^{'} + f_s^{'} A_s^{'} \tag{13}$$

The height of the compression zone is calculated according to the following formula:

$$f_s A_s + \sigma_{\text{WM-PUC}} A_{\text{WM-PUC}} = f_c \left[b_f^{'} \left(h_f^{'} - b \right) + bx \right] + f_s^{'} A_s^{'} \tag{14}$$

To ensure that the reinforcement is suitable for the damage of the beam, the height of the compression zone should meet $2a_s^{'} \leq x \leq \xi h_0$, then the positive section flexural capacity is computed according to the following formula:

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$$\gamma_0 M \le f_c bx\left(h_0 - \frac{x}{2}\right) + f_c\left(b_f^{'} - b\right)\left(h_0 - \frac{h_f^{'}}{2}\right) + f_s^{'} A_s^{'}\left(h_0 - a_s^{'}\right) \tag{15}$$

$$h_0 = \frac{\left[f_s A_s\left(h - a_s\right) + \sigma_{WM\text{-}PUC} A_{WM\text{-}PUC}\left(h - a_{WM\text{-}PUC}\right)\right]}{\left(f_s A_s + \sigma_{WM\text{-}PUC} A_{WM\text{-}PUC}\right)} \tag{16}$$

where γ_0 is the structural importance factor, M is the positive section bending moment, f_s、$f_s^{'}$、f_c is the design value of tensile strength of tensile reinforcement, the design value of compressive strength of erection bars, the design value of concrete compressive strength, A_s、$A_s^{'}$ is the cross-sectional area of the tensile reinforcement and the cross-sectional area of the compressive reinforcement, $A_{WM\text{-}PUC}$、$\sigma_{WM\text{-}PUC}$ is the sectional area of SWM-PUC composite, the tensile stress of SWM-PUC composite, $b_f^{'}$、$h_f^{'}$、b is the width of the top flange of the T-beam, thickness of the top flange of the T-beam, and width of the ribs of the T-beam, h、h_0、x is the height of full section of reinforced T-beam, effective height of reinforced T-beam section, height of pressurized area of section, a_s、$a_s^{'}$、$a_{WM\text{-}PUC}$ is the distance from the tensile reinforcement to the bottom of the beam, the distance from the compressive reinforcement to the upper flange, and the distance from the total stress point of the SWM-PUC composite to the bottom of the beam.

The ultimate bearing capacity values using the above computation method are in good agreement with the test values, with an error of no more than 10%. As presented in Table 5.

Tab. 5 - Comparison of calculated and test values of load capacity

Beam	CB	B3	B4	B5
Test value/kN	80	112.8	122.6	140
Calculated value/kN	78	108	116	132
Error value	2.6%	4.2%	5.5%	6%

Deflection Analysis

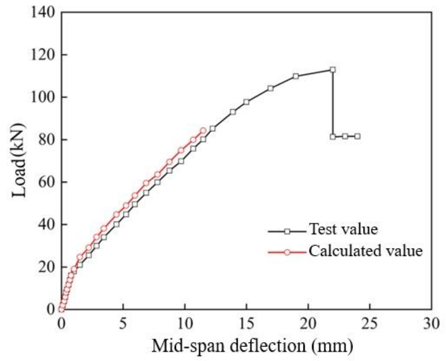
It has been shown experimentally that the load versus deflection curve can be approximated as two linear phases before the reinforcement yields. Therefore, the deflection of the specimens strengthened using the SWM-PUC composite can be accurately computed directly from the bilinear model. The bilinear approach directly maps the load-deflection relationship into two linear approximation expressions. Calculate the partial bending moment M_{cr} before cracking I_0 to obtain the deflection f_1. According to the moment of inertia I_{cr}, calculate the bending moment M'=M-M_{cr} of the other part after cracking to obtain the deflection f_2, and then calculate the total deflection of the specimen as $f=f_1+f_2$. The revised deflection is calculated as follows:

$$f = \lambda l^2\left(\frac{M_{cr}}{\beta_1 E_c I_0} + \frac{M - M_{cr}}{\beta_2 E_c I_{cr}}\right) \tag{17}$$

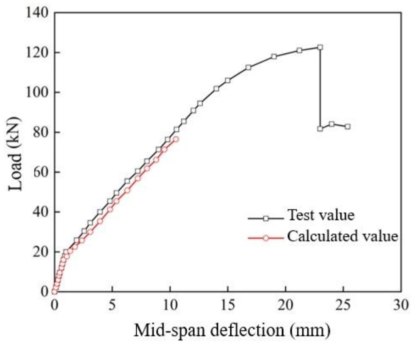
where β_1、β_2 is the influence coefficient, parsing the experimental data by linear regression yielded the influence coefficient β_1=0.95、β_2=0.72. λ is the coefficient of deformation, l is the computed spans of reinforced specimen, M_{cr} is the value of cracking moment, M is the real bending moment value,I_0、I_{cr} is the moment of inertia of the section before and after cracking, E_c is the modulus of elasticity of concrete.

The test results of the SWM-PUC composite strengthened T-beam were contrasted with the calculated results as presented in Figure 11. The corrected deflection calculations were in better agreement with the partial experimental results of the SWM-PUC composite strengthened T-beam.

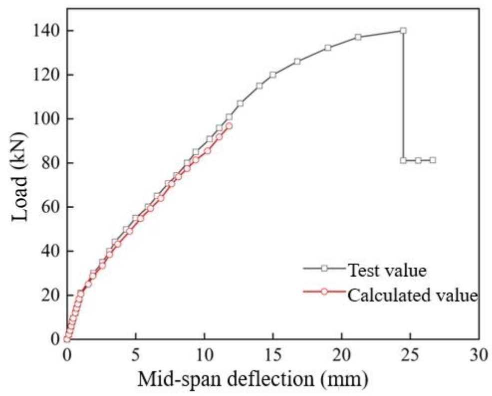
The results show that the equation can be used to compute and predict the deflection of SWM-PUC composite reinforced T-beams in the yield load range.



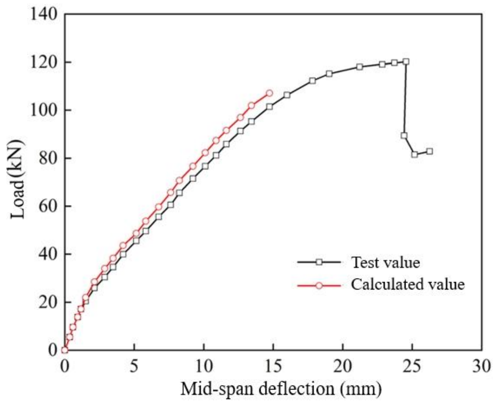
(a) Beam B3



(b) Beam B4



(c) Beam B5



(d) Beam B6

Fig. 11 - Comparison of test and calculated deflections in the yield load range

The ultimate deflection is calculated using the method of structural mechanics, and the deflection of the strengthened test T-beam is computed in accordance with the following equation:

$$B=\frac{B_0}{(\frac{M_{cr}}{M_s})^2+[1-\left(\frac{M_{cr}}{M_s}\right)^2\bigg]\frac{B_0}{B_{cr}}} \tag{18}$$

$$M_{cr}=\gamma f_t W \tag{19}$$

$$\gamma=\frac{2S_0}{W_0} \tag{20}$$

$$f=\frac{243M}{320B} \tag{21}$$

where S_0 is the static torque of T-beam after strengthening in section, γ is the coefficient of plastic influence of tensile zone concrete, W_0 is the moment of elastic resistance at the tension margin, B_0 is the full-section bending stiffness, B_0=0.95E_c+I_0, B_{cr} is the bending stiffness of cracked section, B_{cr}=$E_{cr}I_{cr}$.

The comparison of the deflection values using the above calculation method with the test values as presented in Table 6. The error between the computed value of ultimate deflection and the test value does not exceed 10%, which is within reasonable limits.

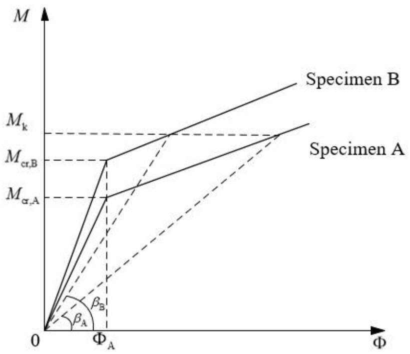
Tab. 6 - The calculated values of deflection are compared with the test values

Beam	CB	B3	B4	B5	B6
Test value/kN	26.1	26.3	27.5	28.8	26.2
Calculated value/kN	25	25.5	26	26.6	24.5
Error value	4.2%	3%	5.5%	7.6%	6.5%

Section Stiffness Analysis

Effect of Reinforcement Ratio of SWM on Strengthened Concrete T-beam

The influence of the reinforcement ratio of the SWM on the section stiffness as presented in Figure 12. Specimen A and specimen B have the same parameters of ordinary steel reinforcement ratio and PUC, but different reinforcement ratios for the SWM. It can be seen from equation (4), the bending moment of cracking of specimen B is larger than the cracking moment of specimen A. Since both specimens had the same reinforcement rate of ordinary steel bars, the two straight lines after cracking had the same slope. At the equivalent bending moment, the lower section rigidity of specimen B is higher than that of specimen A It is observed that the stiffness increases with the increase in the reinforcement ratio of the SWM for the same common steel reinforcement ratio.



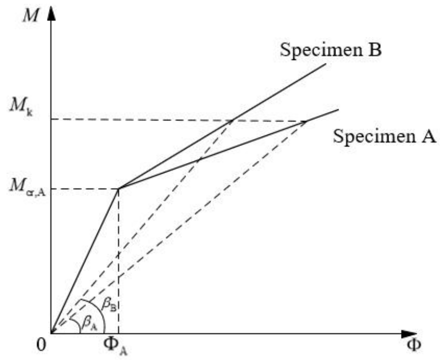


Fig.12 - Effect of reinforcement ratio of SWM on section stiffness

Fig. 13 - Effect of reinforcement ratio of ordinary steel on section stiffness

Effect of Common Reinforcement Ratio on Strengthened Concrete T-beams

The influence of the reinforcement ratio of ordinary steel on section stiffness as presented in Figure 13. The reinforcement ratio of the SWM and the thickness of the PUC of specimen A and specimen B are the same, and the reinforcement ratio of ordinary steel in specimen B is larger than that in specimen A. The bending moment at cracking of specimen A and specimen B are equal. The reinforcement ratio of the section plays a major role in influencing the slope of the line in the second stage after cracking. The greater the ratio is, the greater the slope is. The rigidity of specimen B in the second stage is larger than that of specimen A. Therefore, the cross-sectional stiffness of specimen B will be greater than that of specimen A for the same bending moment.

Effect of PUC on Reinforced Concrete T-beams

The effect of PUC thickness on section stiffness as presented in Figure 14. The reinforcement ratio of the SWM and the reinforcement ratio of the ordinary reinforcement are the same parameters for both specimen A and specimen B, but the thickness of the PUC is different. From the graph, it is clear that the cracking load of specimen B is larger than the cracking load a of specimen. The sectional stiffness of specimen B is greater than that of specimen A. The findings indicate that the use of PUC as a bond anchoring material can appropriately increase the cracking load and rigidity of the second stage.

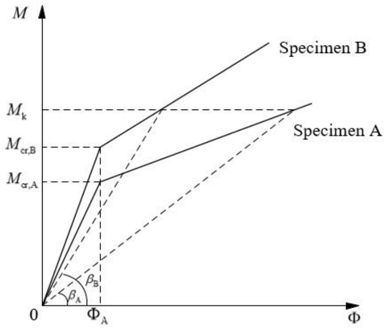


Fig. 14 - Effect of PUC thickness on section stiffness

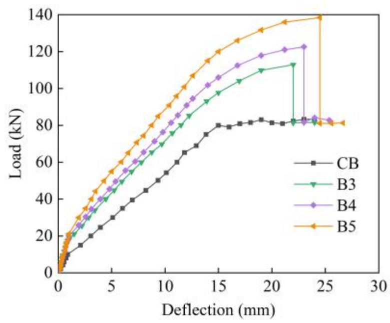


Fig. 15 - Load-deflection curves for CB, B3, B4 and beam B5

Effect of SWM-PUC Strengthening Layer on Reinforced Concrete T-Beam

In order to investigate the influence of using SWM-PUC composite reinforcement on the flexural stiffness of the test beams, the load-deflection curves of beams CB, B3, B4 and B5 were compared, as presented in Figure15. The results show that the SWM-PUC composite reinforcement method can improve the stiffness of plain reinforced concrete T-beams significantly. Largely because: (1) The use of the steel wire mesh increased the cracking load of the beams, thus substantially increasing their service stage stiffness; (2) The use of SWM for reinforcement is tantamount to increasing the reinforcement ratio of the beams, thus increasing the stiffness of the beams during the service phase; (3) PUC has some flexural properties and durability, and it can hold the SWM better, thus increasing the stiffness of the beam.

Crack Width Analysis

Referring to the concrete structure design code [26], the crack width of strengthened concrete is calculated as follows:

$$\begin{aligned} &\varpi_{\max} = \alpha_{cr}\psi \frac{\sigma_{ss}}{E_s}\left(1.9c + 0.08\frac{1+\alpha}{1+\theta}\frac{d_{eq}}{\rho_{te}}\right) \\ &\psi = 1.1 - \frac{0.65 f_{tk}}{\rho_{te}\sigma_{ss}} \\ &\sigma_{ss} = \frac{M_s}{(1+\alpha)A_s\eta h_0} \end{aligned} \tag{22}$$

where a_{cr} is the characteristic coefficient of stress for beam, a_{cr}=1.7, E_s is the elastic modulus of longitudinal reinforcement, c is the thickness of the protective layer, a is the equivalent rigidity coefficients of SWM-PUC composite strengthening layer, θ is the SWM-PUC composite reinforcement layer impact factor, ψ is the reinforcement strain coefficient, when ψ <0.2, let ψ = 0.2, and when ψ >1.0, let ψ = 1.0, f_{tk} is the standard tensile strength of concrete axis, σ_{ss} is the equivalent stress of composite reinforcement in the tension zone, M_s is the value of moment under standard load combinations.

Formulas based on crack spacing and crack width. In this paper, a method of strengthening reinforced concrete T-beams with SWM-PUC composite was presented. Calculations were carried out for beams reinforced with different proportions of SWM reinforcement ratio and PUC thickness, and the results of split width calculations were compared with the measured results, as presented in Table 7. From the table, it is seen that the calculation method of the modified formula matches well with the measured value, and it can be closer to the actual split width than the actual crack width.

Tab. 7 - The calculated value of crack width compared with the test value

Beam	CB	B3	B4	B5	B6
Test value/kN	0.58	0.49	0.48	0.45	0.47
Calculated value/kN	0.54	0.47	0.46	0.44	0.45
Error value	6.9%	4%	4.1%	2.2%	4.3%

CONCLUSION

In view of some problems in the strengthening of reinforced concrete structures by SWM-PM. The composite reinforcement technology combining SWM-PUC material was proposed. To verify the practicability of this composite reinforcement technique, the research on the bending properties of reinforced concrete beams strengthened by SWM-PUC was emphasized, and the main findings were as follows:

(1) The cracking load of the SWM-PUC composite strengthening layer on the test beams was significantly better than that of the SWM-PM strengthening layer. When the thickness of the strengthening layer was 20 mm and eight steel wires were configured. The cracking load of the beams strengthened with SWM-PUC composite was 42.8% higher than that of the beams strengthened with SWM-PM. When there were three fewer steel wires, the cracking load of the SWM-PUC strengthened beam was still 28.6% higher than that of the SWM-PM strengthened beam.

(2) The SWM-PUC composite strengthening was more effective in lifting the yield load of the strengthened beams. The yield load increases with the increase in the reinforcement ratio of the SWM and the thickness of the strengthening layer. When the thickness of the strengthening layer was 20 mm and eight steel wires were configured. The yield load of the beams strengthened with SWM-PUC composite was 22.6% higher than that of the beams strengthened with SWM-PM. At a strengthening layer thickness of 20 mm, increase in steel wires from five to eight. The yield load increase was 8.6%. When eight steel wires were configured, the thickness of the strengthening layer was increased from 20 mm to 30 mm yield load was increased by 24.1%.

(3) The SWM-PUC composite strengthening can effectively enhance the load bearing capacity of the specimens more than the SWM-PM strengthening. And the yield load increased with the increase of the reinforcement ratio of the SWM and the thickness of the strengthening layer. When the thickness of the strengthening layer was 20 mm and eight steel wires were configured. The ultimate load of the SWM-PUC composite strengthening beams was 44.2% higher than that of the SWM-PM strengthening beams. At a strengthening layer thickness of 20 mm, increase in steel wires from five to eight. The ultimate load increase was 8.7%. When eight steel wires were configured, the thickness of the strengthening layer was increased from 20 mm to 30 mm ultimate load was increased by 24.1%.

(4) The theoretical formulas for cracking load, ultimate load, deflection, and crack width of reinforced concrete T-beams strengthened with SWM-PUC composite reinforcement were derived in conjunction with existing codes. The test results are within 10% error of the theoretical calculations.

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