Finite element analysis on flexural performance of the bending capacity for concrete beams reinforced with ECC and aluminum alloy bars

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Abstract. The flexural performance of concrete beams reinforced by engineered cementitious composites (ECC) and embedded aluminum alloy bars was analyzed by finite element method, and compared the results with the existed experimental values to verify the correctness of the finite element model. On this basis, the effects of different ECC reinforcement thickness, the number of aluminum alloy reinforcement roots and the diameter of aluminum alloy reinforcement on improving the flexural performance of the reinforced beams were studied. The results showed that: ECC-aluminum alloy bars reinforcement can significantly improve the flexural performance of reinforced concrete beams, and the ultimate load capacity of reinforced beams was improved by 5.88%~73.66% compared with that of control beams; the effect of ECC-aluminum alloy bars reinforcement method was better than that of reinforcement with ECC material only; the degree of improvement of yield load of beams by ECC reinforcement layer was greater than that of ultimate load; The thickness of ECC reinforcement layer, the number of aluminum alloy reinforcement roots and diameter were proportional to the reinforcement effect of reinforced beams, among which increasing the number of aluminum alloy reinforcement roots had a great influence on the flexural load capacity of reinforced beams, which provided for the calculation of flexural performance of reinforced concrete structures.

Keywords: ECC, aluminum alloy bars, reinforced beam, flexural load capacity.

1. Introduction

Concrete structure in environmental erosion and overload use, bearing capacity and durability performance gradually reduced, if taken to demolition and reconstruction, laborious and not economic and environmental protection, so the concrete structure to strengthen the reinforcement to improve or restore the performance of the structure was extremely important. Previously, the strengthening of members was based on the method of increasing the cross-section and the method of applying steel plates to the surface [1]. In recent years, scholars at home and abroad have carried out systematic experimental research and theoretical analysis on the embedded reinforcement method[2-4], embedded reinforcement was embedded in high performance tendons or sheets after grooving the surface of the structure, and then fill the grooves and smoothen and fix them with cement-based materials or epoxy resin and other adhesive materials to achieve the purpose of strengthening and reinforcing the structure, and the results showed that embedded reinforcement method can effectively enhance the strength and stiffness of concrete structures[5]. Aluminum alloy materials were stronger than steel, only 1/3 of the density of steel, ductile and corrosion resistant, and have been rapidly developed and applied in China's construction projects[6-7].

It has been demonstrated that aluminum alloy material reinforced concrete structures can effectively improve the flexural performance of beams. Zhang et al.[8] tested The flexural behavior of seven reinforced concrete beams strengthened with aluminum alloy plates. It is concluded that compared with the reference RC beam, increasing the thickness of aluminum plates the bearing capacity stiffness by 56% ~ 66%, and decreased the relative slips between aluminum plates and concrete.Abuodeh et al.[9] studied the flexural strengthening of RC beams using aluminum alloy plates with mechanically-fastened anchorage systems.The test results indicated that the strength and ductility stiffness of

reinforced concrete beams strengthened with aluminum alloy plates can be effectively increased. Li et al.[10] designed and tested eight RC beams strengthened with prestressed near-surface mounted 7075 aluminum alloy bars. Results indicate that the application of the strengthening system was able to prevent premature debonding failure and increase the load-bearing capacity by up to 102.1%.

ECC (Engineered Cementitious Composite) materials have ultra-high toughness and provide sufficient bonding force when reinforced, and also solve the problem of poor durability performance of organic interface paste, which can effectively inhibit cracking [11-13]. Existing studies have confirmed that the application of ECC material to concrete structure reinforcement can improve the flexural load capacity of the beam[14-16].The combination of the ECC layer and the steel plate on the RC beam significantly delayed the formation and development of cracks, thereby enhancing the over-reinforcement of the steel RC beams, as well as increasing their flexural capacity and ductility[17]. Hamoda tested and numerically analyzed the concrete beams strengthened with ECC and stainless steel strip.The experimental results demonstrated that hybrid SS-ECC strengthening can improve the ultimate capacity of NC beams by as much as 156%[18].

In the paper, the structure was reinforced by using ECC material as the reinforcement layer at the bottom of the reinforced beam, and the aluminum alloy reinforcement was embedded in ECC to verify the reinforcement effect by means of finite element simulation.

2. BASIC THEORY

2.1. Model of control beam and reinforcement beam

The article performed finite element analysis of reinforced concrete beams and compares the results with the test beams in the literature[19]to verify the correctness of the model.The dimensions of the reinforced concrete beam model were shown in Fig.1. The concrete beam was reinforced with ECC material and aluminum alloy reinforcement composite, the ECC material was pasted at the bottom of the beam, the width of the ECC reinforcement layer was b, the aluminum alloy reinforcement was located in the middle of the ECC material thickness, the beam cross-sectional dimensions were shown in Fig. 2

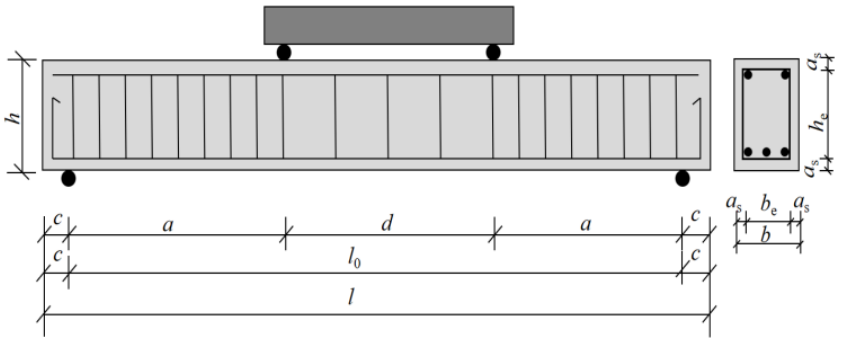


Figure 1. Section dimension diagram of the control beam

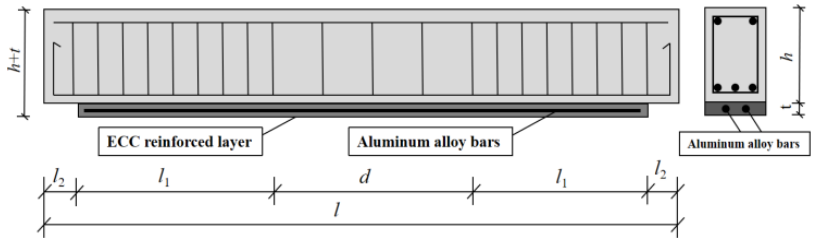


Figure 2. Section dimensions of the reinforced beam

2.2. Unit type

ABAQUS three-dimensional finite element model was used for the analysis. The concrete was constructed using three-dimensional eight-node linear reduced integral unit (C3D8R), and the plastic

damage model was used in the establishment of the finite element model because its plastic deformation was obvious before the failure of the concrete.When defining the properties of ECC materials, considering that both ECC materials and concrete were cementitious composites, the properties of ECC reinforcement layer materials are also defined using C3D8R units and plastic damage model.Both steel and aluminum alloy reinforcement were used in linear truss unit (T3D2). Considering the tensile strengthening phase of the steel reinforcement, the bilinear model was selected in the paper for the steel reinforcement, and the aluminum alloy reinforcement was the high strength aluminum alloy reinforcement of T7075 series.

2.3. Contact processing

In order to prevent the computational non-convergence caused by the stress concentration of the unit during the load application, steel mat plate was set at the bearing and the load should be added, and the mat plate still adopts the C3D8R unit, and the steel mat plate and concrete are coordinated to deform each other by setting the common node, and a reference point was mainly set on the mat plate when simulating the loading, so that the steel mat plate was coupled with the reference point. Without considering the slip between the mat and the concrete beam, the contact surface was set to be constrained by Tie, and the concrete beam was also bound to the ECC reinforcement layer by Tie. The restraint mode of the built-in area was used between the steel skeleton and the concrete, and the bonding mode between the aluminum alloy reinforcement and the ECC material also adopts the interface restraint mode of the built-in area.

2.4. Boundary conditions

Displacement-controlled loading of concrete beams was achieved by applying displacement on the reference points on the pad. Displacement loading can reduce the convergence difficulty, and the hinge support of concrete beams was simulated in the paper by constraining the degrees of freedom of the pad, with fixed hinge on one side and sliding hinge on the other side.

2.5. Constitutive relations of materials

The Ramberg-Osgood model has been widely used in the study of the intrinsic structure relationship of metal structures, and the modified Ramberg-Osgood model was used for aluminum alloy tendons in the paper [20]:

$$\varepsilon = \frac{\sigma}{68000} + 0.002\left(\frac{\sigma}{f_{0.2}}\right)^{0.1 f_{0.2}} \tag{1}$$

The ECC uniaxial tensile principal structure uses a simplified bilinear model [21]as shown in Fig.3, with the expression:

$$\sigma_t = \begin{cases} \dfrac{\sigma_{tc}}{\varepsilon_{tc}}\varepsilon_t & ,0 \le \varepsilon_t \le \varepsilon_{tc} \\ \sigma_{tc} + \dfrac{\sigma_{tu}-\sigma_{tc}}{\varepsilon_{tu}-\varepsilon_{tc}}\left(\varepsilon_t - \varepsilon_{tc}\right) & ,\varepsilon_{tc} \le \varepsilon_t \le \varepsilon_{tu} \end{cases} \tag{2}$$

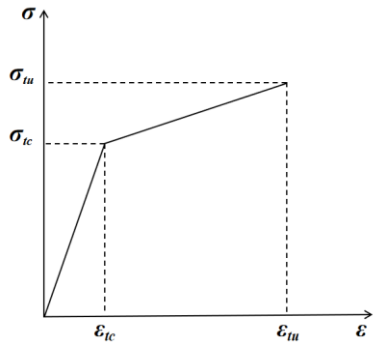


Figure 3. ECC material pull-configuration

3. Analysis of calculation cases

3.1. Finite-element model validation

Finite element analysis was carried out to verify the correctness of the model for the reinforced concrete test beam CL-30 in the literature[19] , the concrete strength grade of the test beam was C30, the length of the beam was 2700mm, the cross-sectional dimensions were b=150mm, h=250mm, the beam tension main reinforcement was 3A14, the compression reinforcement was 2A8, the hoop reinforcement in the encrypted zone was A6@100, the non-encrypted zone was A6@200 The concrete protective layer thickness was as=25mm, the loading point distance from the support a=800mm, the two loading points distance b=800mm, the width of ECC reinforcement layer was 150mm, the length was 2200mm, the reinforced beam cross-sectional dimensions were shown in Fig.4, the mechanical properties of concrete, reinforcement, ECC material and aluminum alloy reinforcement were detailed in Table 1-3.

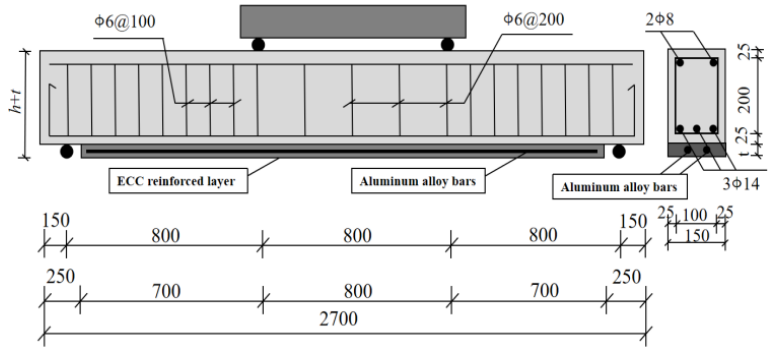


Figure 4. Cross-sectional dimensions of control beam CL-30

Table 1. Mechanical properties of concrete and rebars

Material		Yield Strength/MPa	Ultimate Strength /MPa	Elastic Modulus /GPa
Concrete			40.3	32.7
Rebars	A8	352.1	523.9	200
	A14	365.9	535.9	210

Table 2. Mechanical properties of ECC

Material	Compressive Strength /MPa	Cracking Strength /MPa	Elastic Modulus /GPa
ECC	51.84	5.14	20.73

Table 3. Mechanical properties of aluminum alloy bars

Material	Yield strength /MPa	Ultimate strength /MPa	Elastic modulus /GPa
Aluminum alloy bars	528.4	589.7	72.7

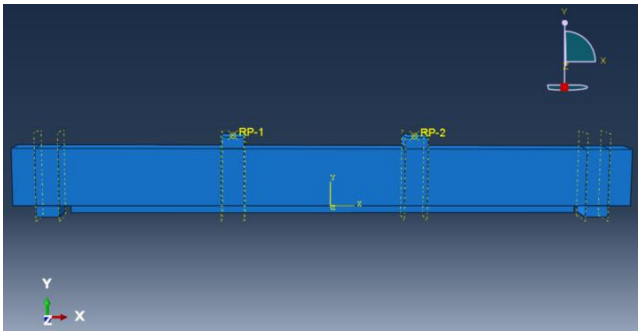


Figure 5. Finite element model of the reinforced CL30 beam

Simulations were performed for the reinforced concrete beam CL30 to verify the agreement between the simulated and tested values. The simulation results were compared with the experimental results to verify the scientific nature of the model, and the simulation results were shown in Fig. 6

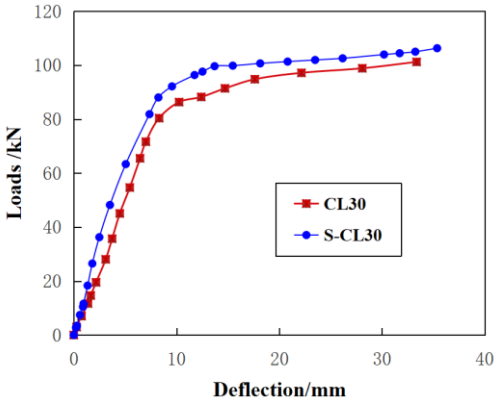


Figure 6. Middle displacement curve of the load span of the beam

Table 4. Comparison of test values and simulated values of CL 30 beam

Data name	Literature test value [19]	Analog value	Error
Yield load	85	92.04	8.28%
To yield deflection	10.02	9.56	4.59%
Ultimate load	102	106.28	4.28%
Extreme deflection	33.4	35.36	5.87%

The CL30 curve represents the test results of the unreinforced beam, and S-CL30 was the finite element simulation result. According to the above data, it can be seen that the simulated load curve of the unreinforced beam basically matches with the test results, and the simulated value of S-CL30 was slightly larger than that of the CL30 beam at the early stage of loading, which was because during the test process, the reinforcement will appear bond slip during the loading process, and the finite element modeling was applied to the ABAQUS simulations reflect the experimental beam stiffness better than the test beam stiffness, and the errors of cracking load and breaking load were within 8%, which was allowable for numerical simulation. The ABAQUS simulations reflect the stress state of the experimental beam better and prove the feasibility and accuracy of the model.

3.2. Effect of different reinforcement methods on the flexural load capacity of concrete beams

ABAQUS software was used to further explore the effect of different ECC-alloy reinforcement composite methods on the flexural load capacity of the beams.The design table of reinforced concrete beams with ECC-alloy reinforcement composite was shown in Table 5.

Table 5. Design of reinforced concrete beams with ECC-aluminum alloy bars reinforcement composite

Test piece number	ECC layer (mm)	Aluminum alloy bars	Aluminum alloy tendon diameter (mm)
S-CL30	None	None	None
S-CL30-E30	30	None	None
S-CL30-E30-A1	30	1	14
S-CL30--E30-A2	30	2	14
S-CL30--E30-B1	30	1	16
S-CL30-E40	40	None	None
S-CL30-E40-A1	40	1	14
S-CL30--E40-A2	40	2	14
S-CL30--E40-B1	40	1	16

Table 6. Finite element analysis results of lower beams under different strengthening methods

Test piece number	The yield state			Limit condition		
	Load (kN)	Deflection (mm)	Promote (%)	Load (kN)	Deflection (mm)	Promote (%)
S-CL30	92.04	9.56	—	106.28	35.36	—
S-CL30-E30	103.1	9.67	12.02%	112.53	30.41	5.88%
S-CL30-E30-A1	127.74	12.75	38.79%	147.29	27.41	38.59%
S-CL30--E30-A2	137.11	11.26	48.97%	178.11	25	67.59%
S-CL30--E30-B1	129.02	12.05	40.18%	159.09	26.53	49.69%
S-CL30-E40	106.80	9.81	16.04%	115.80	27.12	8.96%
S-CL30-E40-A1	130.88	12.75	42.20%	152.76	25.67	43.73%
S-CL30--E40-A2	143.42	12.19	55.82%	184.57	24.11	73.66%
S-CL30--E40-B1	133.03	12.21	44.53%	160.09	24.41	50.63%

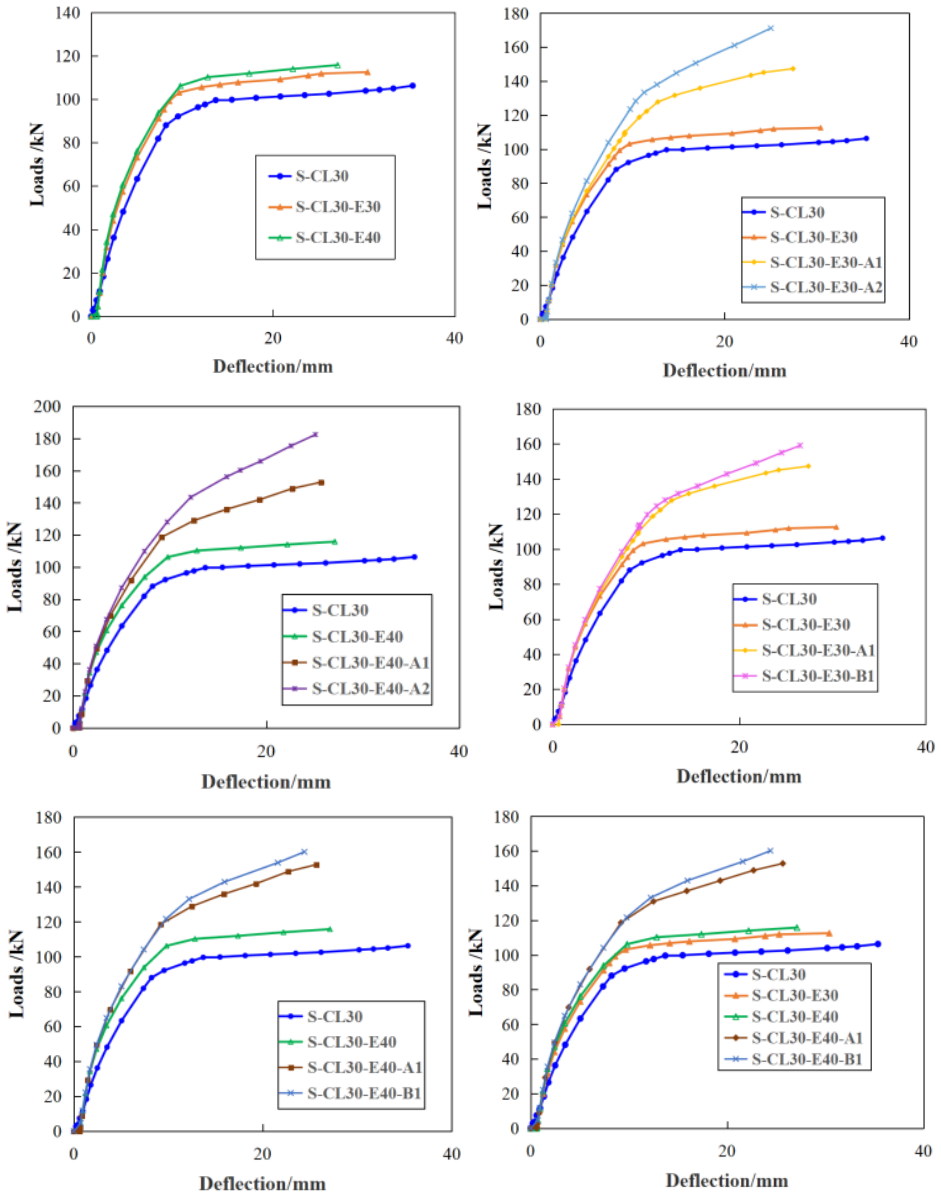


Figure 7. Load displacement curve of reinforced concrete beam with ECC-aluminum alloy reinforcement composite

As seen in Table 6 and Fig. 7, when the concrete beams were strengthened with ECC materials alone, the yield strength of the strengthened beams were 103.1 and 106.8 kN and the ultimate load was

112.53 and 115.8 kN when the thickness of ECC reinforcement layer was 30 mm and 40 mm, respectively, which increased the yield load by 12.02% and 16.04%, respectively, and the ultimate load compared with the control beam increased by 5.88% and 8.96%, respectively. The degree of ECC material to improve the yield load of the beam was somewhat greater than the degree of ultimate load improvement, which was because the ECC reinforcement layer has the main effect on the cracking load and crack expansion.

With the same thickness of ECC and increasing the number of aluminum alloy reinforcement for reinforcement, the yield load of beam S-CL30-E30-A1 and beam S-CL30-E30-A2 increased by 38.79% and 48.97%, and the ultimate load increased by 38.59% and 67.59%, respectively, compared with the control beam, and the yield load of beam S-CL30-E40-A1 and beam S-CL30-E40-A2 increased by 42.20% and 55.82%, and the ultimate load increased by 43.73% and 73.66%, respectively, compared with the control beam. E40-A2, the yield loads increased by 42.20% and 55.82%, and the ultimate loads increased by 43.73% and 73.66%, respectively, compared with the control beams. It can be seen that the effect of using ECC-aluminum alloy reinforcement composite to strengthen concrete beams was much better than that of using ECC material alone, and increasing the number of aluminum alloy reinforcement roots was effective in improving the flexural performance of the strengthened beams.

With the same thickness of ECC and the same number of aluminum alloy reinforcement bars, the yield load and ultimate load of 16mm diameter aluminum alloy reinforcement beam S-CL30-E30-B1 was 129.02kN and 159.09kN, compared with the yield load and ultimate load of 14mm diameter aluminum alloy reinforcement beam S-CL30-E30-A1 were increased by 1.01% and 8.01%, respectively. The yield load of beam S-CL30-E40-B1 was 133.03kN and the ultimate load was 160.09kN, compared with the yield load and ultimate load of beam S-CL30-E40-A1, the yield load and ultimate load were increased by 1.64% and 4.80% respectively, it can be seen that increasing the diameter of aluminum alloy reinforcement can improve the flexural load capacity of the reinforced beam, but the improvement effect was not obvious.

4. Conclusion

In the paper, the mechanical properties of ECC-alloy reinforced composite reinforced concrete beams were studied to investigate the effects of different ECC reinforcement layer thickness, number of aluminum alloy bars, diameter of aluminum alloy bars and other factors on the flexural load capacity of reinforced beams, and the following conclusions are obtained:

The ultimate load carrying capacity of the reinforced beam is increased by 5.88%~73.66% and the deflection was reduced by 14.01%~31.82% compared with the comparison beam. The ultimate flexural load carrying capacity and flexural stiffness of the concrete beam can be improved by using ECC material alone and by using ECC-aluminum alloy reinforcement. The mechanical properties of beams reinforced with ECC-aluminum alloy reinforcement were significantly better than those of beams reinforced with ECC alone, which provided a reference for the application of ECC-aluminum alloy bars reinforcement composite structure.

Compared with the control beam, the yield load was increased by 12.02% to 16.04% and the ultimate load was increased by 5.88% to 8.96% with ECC material reinforcement alone, respectively. The degree of yield load improvement of the beam by ECC material was somewhat greater than the degree of ultimate load improvement because the ECC reinforcement layer had a major effect on the cracking load and crack expansion.

The longitudinal tensile force of ECC-aluminum alloy reinforced beam was mainly borne by aluminum alloy reinforcement and ECC material after the steel has yielded. The thickness of ECC reinforcement layer, the number of roots and diameter of aluminum alloy reinforcement were proportional to the reinforcement effect of reinforced beam, in which increasing the number of roots of aluminum alloy reinforcement has a greater influence on the ultimate bearing capacity and flexural stiffness of reinforced beam.

Acknowledgments

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References

[1] Charlei Marcelo Paliga,Natiele Gonçalves Nicolini,Aline Ribeiro Paliga,Ariela da Silva Torres (2019) Experimental study of reinforced concrete beams strengthened for flexure with steel plates. Revista de Engenharia Civil IMED (1).

[2] Bhanugoban Maheshwaran,Yapa Hiran D.,Dirar Samir (2021) Efficient shear retrofitting of reinforced concrete beams using prestressed deep embedded bars. Engineering Structures.

[3] Jabbar Fatima Sattar,Resan Sa'ad Fahad (2021) Composite reinforced concrete beam of embedded double skin steel plates. Journal of Physics: Conference Series (1).

[4]]Yajun Zhao,Yimiao Huang,Haiyang Du, Guowei Ma (2020) Flexural behaviour of reinforced concrete beams strengthened with pre-stressed and near surface mounted steel–basalt-fibre composite bars. Advances in Structural Engineering(6).

[5] Barris C, Sala P, Gómez J et al (2020) Flexural behaviour of FRP reinforced concrete beams strengthened with NSM CFRP strips. Composite Structures(prepublish).

[6] L.P.Yang,S.Wei,Q.L.Zhang (2013) Aluminum reticulated spatial structures:state of the art and key issues . Journal of Building Structures 34(2):1 − 19 [In Chinese]

[7] Y.Zhang,Y.Q.Wang,J.G.Zhang et al (2020) Finite element analysis of single-limb mechanical behavior of box-i-shaped disk joints of aluminum alloy latticed shells. Applied Mechanics 37(Supplement 1): 130 − 138 [In Chinese].

[8] Z.Zhang,Y.T.Liu ,L.L.Zhi, Z.D.Lu (2022) The use of bolted side aluminum alloy plates for flexural capacity of reinforced concrete beams: An experimental investigation. Structures.

[9] Abuodeh Omar R,Abdalla Jamal A,Hawileh Rami A (2021) Flexural strengthening of RC beams using aluminum alloy plates with mechanically-fastened anchorage systems: An experimental investigation. Engineering Structures.

[10] X.Y.Li, G.H.Xing, Z.Q.Chang et al (2023) Experimental and analytical study of RC beams strengthened with prestressed near-surface mounted 7075 aluminum alloy bars. Structures.

[11] T.Jun,X.W.Wu,T.Xiao et al (2022) Experimental study and analysis model of flexural synergistic effect of reinforced concrete beams strengthened with ECC. Construction and Building Materials.

[12] Awad Fady,Husain Mohamed,Fawzy Khaled (2022) Flexural behaviour of reinforced concrete beams strengthened by NSM technique using ECC. Fracture and Structural Integrity:International Journal of Italian Group of Fracture(60).

[13] L.N.Deng,Y.Zhou,M.J.Zhong et al (2023) Deflection of RC beams strengthened with FRP mesh-ECC composites . Journal of Composite Materials:1-14 [In Chinese].

[14] Lim Chhoung,Jeong Yeongseok,Kim Jinsup,Kwon Minho (2022) Experimental study of reinforced concrete beam-column joint retrofitted by CFRP grid with ECC and high strength mortar. Construction and Building Materials.

[15] Y.X.Zhang,M.K.Deng,T.Li,Z.F.Dong (2021) Strengthening of flexure-dominate RC columns with ECC jackets: Experiment and analysis. Engineering Structures.

[16] W.Guan,F.W.Zhu,C.Q.Yang (2020) Experimental study on Shear behaviors of RC beams strengthened with ECC layers. IOP Conference Series: Materials Science and Engineering 780(4)

[17] L.Long,S.S.Yu ,X.P.Ma (2023) Flexural capacity of RC beams reinforced with ECC layer and steel plate. Journal of Building Engineering.

[18] Hamoda Ahmed,Emara Mohamed,Abdelazeem Fathi,Ahmed Mizan (2022) Experimental and numerical analysis of RC beams strengthened with ECC and stainless steel strips. Magazine of Concrete Research.

[19] W.W.Wang,G.F.Zhao, C.K.Huang et al (2004) Experimental study on flexural behavior and calculation of flexural capacity of RC beams strengthened with CFRP sheets. Applied Mechanics 04:172-178 [In Chinese].

[20] GB 50010-2010 (2010) Code for design of concrete structures. Beijing,China

[21] X.N.Guo,S.Z.Shen,Y.Q.Li (2007) Study on the principal structure relationship and physical and mechanical properties of domestic structural aluminum alloy materials[J]. Journal of Building Structures 06:110-117 [In Chinese].

[22] W.J.Ge,Y.F.Zong,S.W.Qiu et al (2021) Study on flexural behavior of BFRP reinforced-ECC-concrete composite beams strengthened with carbon fiber sheets Journal of Building Structures 42(S1) : 302-311 [In Chinese].

[23] X.G.Yu,G.H.Xing,Z.Q.Chang (2020) Flexural behavior of reinforced concrete beams strengthened with near-surface mounted 7075 aluminum alloy bars. Journal of Building Engineering(prepublish).

[24] G.H.Xing,X.Y.Li,Z.Q.Chang,Ozbulut Osman E (2022) Behavior of RC Beams Strengthened with Near-Surface Mounted Aluminum Alloy Bars under Fully Reversible Cyclic Loads. Journal of Bridge Engineering(11).