DESTRUCTIVE TESTING OF TWENTY-YEAR-OLD PRESTRESSED CONCRETE BRIDGE BEAMS IN FREEZING-THAWING REGION

LIU Jin-liang, JIA Yan-min[*]

Northeast Forestry University, School of Civil Engineering, Harbin, 150040, China; jinliangliu_2015@126.com; yanminjia2008@126.com

ABSTRACT

The paper conducted a destructive test and nonlinear finite element analysis for four pieces of pre-stressed concrete hollow plate, which have served for 20 years in the freezing-thawing region. The results showed that typical bending destruction occurred in the test beams under the action of bending load, and the bearing capacity of the test beams decreased by a little compared with finite element analysis results. The test beams showed typical bending response before the reinforcement yielded under the action of uniform load, and the pre-stressed reinforcement in the bending-shearing zone slipped after reinforcement yielded, the final ultimate bearing capacity of the test beam was only 75% of the finite element calculation value.

KEYWORDS

Pre-stressed concrete beam, In-service bridge, Freezing-thawing region, Destructive test, Ultimate bearing capacity, Nonlinear finite element analysis

INTRODUCTION

For the bearing capacity regression law of the in-service bridge is difficult to be obtained from traditional theoretical analysis and test on model beams, because it is hard to precisely simulate the complex conditions of the in-service site. At present, there are two kinds of methods that are most direct and effective for the research of the topic: firstly, a destructive test for an entire real bridge; secondly, a single-beam destructive test for the in-service components. However, due to such factors as difficult acquisition of the test object and high cost, the present research of destructive test on the real bridge and components having served for many years are quite limited. Restricted by test conditions, the scholars made few researches for the destruction theory for an in-service bridge [1-11], but they also made contribution for the design theory of bridge. The testing measures were increased for the recent years, and the theory calculation was improved with high precision. Melchers[12] taken out a destructive test for the rusted pre-stressed concrete beam that has served for 45 years; Olaszek[13] established a time-varying calculation formula on the bearing capacity of an in-service bridge, and verified the applicability of the formula through the load tests on three bridges; Yuan[14] carried out a destructive test for 2 pieces of 20m pre-stressed concrete hollow plate removed from expressway, obtained the law of the stress performance of structure based on the effect of the longitudinal crack on web. Xiang [15] conducted a research on the destruction theory and ultimate bearing capacity of 2 pieces of 20m post-tensioned pre-stressed concrete hollow plate that have served for 11 years, in addition, verified the rationality of the calculation on the ultimate bearing capacity given in the Chinese bridge design specifications.

Due to the diversity of structural type, otherness of service time and load, and disunity of construction criteria, etc., the research on the regression law of the bearing capacity of an in-service bridge is still at the preliminary stage. Therefore, the paper conducted a single-beam

--

destructive loading test for four pieces of 16m pre-stressed concrete hollow plate that have served for 20 years. Furthermore, a nonlinear finite element analysis was carried out for the entire test process based on the actually measured performance indices of material. The research achievements can provide theoretical basis for the optimized design of a new same type of pre-stressed bridge and the maintenance & consolidation of the existing old bridge.

THE INTRODUCTION OF TEST BEAMS

The bridge where the test beams are located was built in 1995, and it lies within Shenyang-Siping Section of G1 Expressway of China, it is a freezing-thawing region in Northeast China. The highest temperature reached 35℃ in summer, and the lowest temperature in winter reached -25℃, the annual highest temperature difference reached 60℃ [16]. The calculation span of the test beam is 15.6m, the oblique crossing angle is 90°, the width is 99cm and the height is 70cm. A circle with diameter of 50cm was cut out from the centre, the thickness of top plate is 8cm, the thickness of bottom plate is 12cm and hollow plate was cast by C40 concrete. The prestressed steel strands of the test beam applies ϕ_j 15.24 （7ϕ5） type, the standard strength is 1,860Mpa and the tensioning control stress is 1,395Mpa, the longitudinal non-prestressed reinforcement applies HRB335 type, with diameter of 12mm; the stirrup applies R235 reinforcement with diameter of 8mm; The following Figure 1 shows the structural drawing on the reinforcement and section of the test beam.

(a) vertical section

NO.	1	2	3	4	5	6
Length	1596	1460	1190	1060	930	790
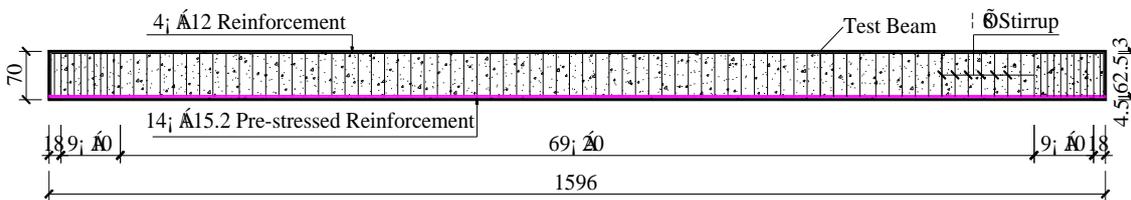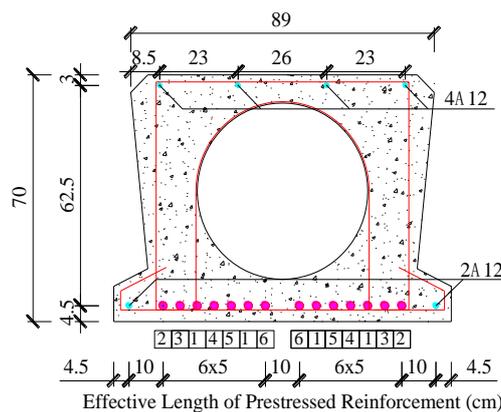
(b) cross section

Fig. 1 - Dimensions and reinforcement of tested beams (Unit: cm)

TEST ON MATERIAL STRENGTH AND DURABILITY EXAMINATION OF THE TEST BEAMS

In order to obtain the durability parameters of the test beam and the strengths of building materials, the concrete carbonation depth, rusting electric potential of reinforcement and concrete defects of the test beams were investigated and measured before carrying out the loading test. After the test beams were destructed, the concrete with low stress was cored for the compressive strength test. Then the concrete of test beams was broken, and common reinforcement and pre-stressed reinforcement were sampled and tested.

Test on material strength of the test beams

The test beams were produced in the same batch, and the working environment and loading status of them during the in-service period are basically consistent. Though material sampling and testing were carried out for each test beam, due to numerous data and small discreteness, the paper arranged various test data of material from small to large, the intermediate three groups of test data on each kind of material are shown in Tables 1-4.

Tab. 1 - Mechanical property of concrete

Specimens No.	Specimens Length (mm)	Specimens Diameter (mm)	Ultimate Load (kN)	Compressive strength (MPa)
NO.1	100	100	364.5	46.4
NO.2	102	100	358.8	45.7
NO.3	97	100	334.9	42.7
Av.	100	100	352.7	44.9

Tab. 2 - Mechanical property of prestressed reinforcement

Specimens No.	Ultimate load (kN)	Ultimate strength (MPa)	Elongation (%)	Elastic modulus (MPa)
NO.1	272.0	1940	6.5	210371
NO.2	271.4	1940	5.0	194414
NO.3	270.1	1930	7.0	208365
Av.	271.2	1937	6.2	204383

Tab. 3 - Mechanical property of reinforcement

Specimens No.	Yield load (kN)	Yield strength (MPa)	Ultimate Load (kN)	Ultimate strength (MPa)
NO.1	42.8	380	55.9	495
NO.2	44.8	395	56.6	500
NO.3	44.0	390	55.8	495
Av.	43.9	388	56.1	497

Tab. 4 - Mechanical property of stirrup

Specimens No.	Yield load (kN)	Yield strength (MPa)	Ultimate Load (kN)	Ultimate strength (MPa)
NO.1	13.8	275	27.2	540
NO.2	13.8	275	27.1	540
NO.3	13.6	270	26.1	520
Av.	13.7	273	26.8	533

The test results of materials in the Tables 1-4 were compared with the performance requirements of material in Code for design of highway reinforced concrete and prestressed concrete bridges and culverts (JTG D62-2004) [17], it was found that the relevant material performances of the test beams that have served for 20 years in the freezing-thawing region can meet the performance requirements specified in the design.

Durability of test beams

Before conducting the lading test, steel ruler was used to measure the sizes of the cross section of the test beam and the sizes were rechecked by drawing. The initial crack was monitored by detection, and no crack was found in the test beams. Procep profometer5+ concrete & reinforcement detector was used to detect the thickness of concrete protection layer of the test beam. Procep canin⁺ reinforcement rusting instrument was used to detect reinforcement rusting of the test beam in all round. The carbonized depth of concrete was tested for the both sides of web and bottom plate of test beams. According to the detection results and in contrast with Chinese Specification for inspection and evaluation of load-bearing capacity of highway bridges (JTG/TJ21-2011)[18], the ratio of the carbonized depth of the test beam and the thickness of concrete protection layer is less than 0.5, the effect of carbonization on the durability of structure is slight. According to the testing value of the rusting electric potential, it can be judged that the reinforcement in the end area of the test beam is rusting-active, and the reinforcement in the beam has not rusting activity in other area.

LOADING TEST AND NUMERICAL SIMULATION ANALYSIS OF TEST BEAMS

The program of loading test

To study the response of the tested beams under the bending load, the beams subjected to pure bending load segment at 2m scheme, i.e. FL=2.0m, the test beams were named as M2-1 and M2-2, respectively. In order to obtain the response of the test beam under the uniform load, the paper carried out the classical Trisection Point Loading Test for structure [19], i.e. FL=5.2m, the test beams were named as M5.2-1 and M5.2-2, respectively. The following Figure 2 shows the details of loading test.
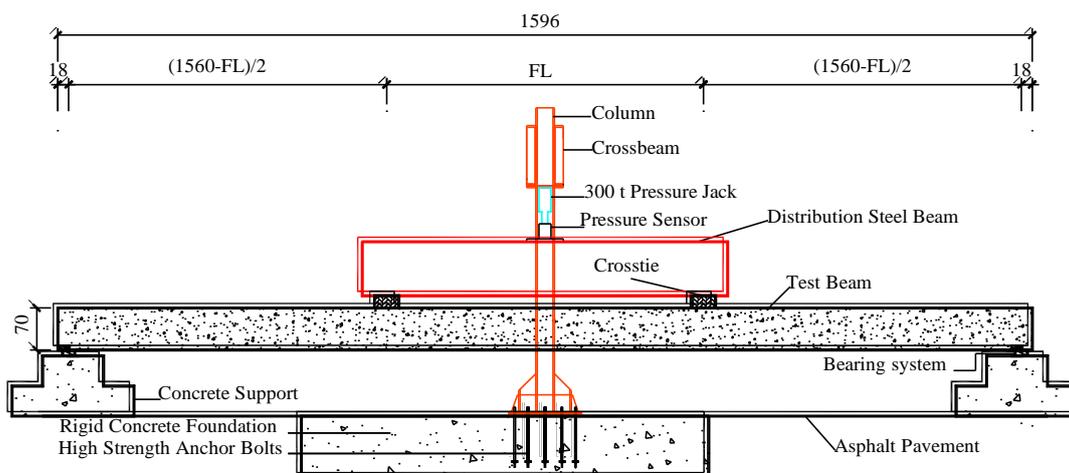

Fig. 2 - Details of loading test (Unit: cm)

Numerical simulation analysis on test beam

ANSYS was adopted to simulate the loading test in this paper, and the value of finite element analysis was compared with the results of the loading test. Concrete adopted Solid65 element, common reinforcement and pre-stressed reinforcement adopted Link8 element for simulation. For the finite element model, temperature decrease method was adopted for exerting pre-stress, and the Code for design of highway reinforced concrete and pre-stressed concrete bridges and culverts (JTG D62-2004) [17] was used to calculate the pre-stress loss. The bearings and the loading plate adopted Solid45 element for simulation, so as to prevent the concrete at bearings, tensioning ends and loading places from being destructed ahead of time.

The loading process of the structure components changed from linear to nonlinear behaviour, so nonlinear analysis was calculated. In the process of establishing the model of the loading test, the slippage between pre-stressed reinforcement and concrete was not considered.

DISCUSSION ON LOADING TEST RESULTS

Description on destruction phenomena

The destruction process of the test beam M2-1 and M2-2 are similar and divided into three stages: stage 1: reversed deflection had existed in the beam before cracks appeared. Following the increase of load, the reversed deflection decreased and disappeared, and the deflection kept linear growth, this phenomenon shows that the structure lay in the stage of elastic operation. Stage 2: the test beams cracked to the yielding stage of common reinforcement. When the test beam M2-1 and M2-2 continued to be loaded until approximate 221kN and 240kN, the concrete at the bottom edge of the pure bending segment firstly cracked vertically, thereafter, the quantity of such vertical crack increased continually and the cracks grew, the vertical crack appearing during the early period unceasingly expanded and extended upwardly, and U-shape crack formed at last. When the test beam M2-1 and M2-2 were loaded to 351kN and 362kN, oblique crack started to appear in the web between the loading point of the shearing-bending segment and bearing, in addition, the crack extended obliquely toward the direction of the loading point from the edge at beam bottom. At the same time, the vertical crack in the purely bending segment continued to extend upwardly. The extension of oblique crack in the shearing-bending segment gradually quickened after the growth of vertical crack in the purely bending segment gradually reached stable state. The lateral crack in the bottom plate connected together and formed U-shape crack at last. Stage 3: common reinforcement yielded to structure destruction stage. When the test beam M2-1 and M2-2 were loaded to 416.5kN and 447.6kN, the common reinforcement in the tensioning zone yielded and failed. When load was exerted continually, the midspan deflection of the test beam became large quickly, the crack became wide quickly. Finally, the concrete in the compressive zone of the purely-bending segment was crushed (as shown in Figure 3(a) and Figure 3(b)). The ultimate load corresponding to the failure of M2-1 and M2-2 are respectively 564kN and 572kN. After the test beam failed, the concrete in the bottom plate of the purely-bending segment was chiselled away, the status of pre-stressed reinforcement was observed, it was found that the pre-stressed reinforcement was not broken. As described above, the test beam M2-1 and M2-2 are typical anti-bending destruction of normal section, which belongs to plastic failure.

The destruction process of the test beam M5.2-1 and M5.2-2 are similar and divided into three stages: The first stage is the same as the stage 1 of the destruction process of the test beam M2-1 and M2-2. Stage 2: the test beams cracked to the yielding stage of common reinforcement. When the test beam M5.2-1 and M5.2-2 continued to be loaded until approximate 315kN and 298kN, the concrete at the bottom edge of the purely bending segment firstly cracked vertically, thereafter, the quantity of such vertical crack increased continually and the cracks grew, the

----

vertical crack appearing at the early period unceasingly expanded and extended upwardly. And U-shape crack formed at last of this stage. Oblique crack started to appear in the web between the loading point of the shearing-bending segment and bearing when the test beam M5.2-1 and M5.2-2 were loaded to 365kN and 321kN. In addition, the crack extended obliquely toward the direction of the loading point from the edge at beam bottom, following the continual increase of load, the extension of oblique crack in the shearing-bending segment gradually quickened, until the oblique crack and the lateral crack in the bottom plate connected together and formed U-shape crack. At the same time, the vertical crack in the purely bending segment continued to extend upwardly and slowly. Stage 3: common reinforcement yielded to structure destruction stage. When the test beam M5.2-1 and M5.2-2 were loaded to 518.3kN and 545.1kN, the common reinforcement in the tensioning zone yielded and failed. After this load, the width and height of vertical crack in the zone of bending moment failed to grow continually. However, the width of oblique crack in the bending-shearing zone of the test beam quickly increased. Moreover, it was found that pre-stressed reinforcement at the end of the test beam apparently slipped, and the concrete in the bottom plate of the test beam crushed and fell off, simultaneously, the deflection and concrete strain near to the loading point on this side quickly increased. Finally, shearing-compression failure appeared on the slippage side of the pre-stressed reinforcement of the test beam (as presented in Figure 4(a) and Figure 4(b)). The ultimate load corresponding to the failure of M5.2-1 and M5.2-2 are respectively 565.7kN and 565.9kN. After the test beam failed, the concrete in the bottom plate of the shearing-bending segment was chiselled away, it was found that the pre-stressed reinforcement apparently slipped inside concrete, which was a bond failure. After serving in freeze-thaw area for 20 years, the corrosion of pre-stressed reinforcement and the freeze-thaw damage of concrete led to insufficient bonding force, but the anchorage of prestressing reinforcement insufficient at the design stage. As described above, the test beam M5.2-1 and M5.2-2 are atypical shearing-compression destruction caused by the slippage of pre-stressed reinforcement, which belongs to brittle failure.

Fig. 3(a) - Failure state of beam M2-1   *Fig. 3(b) - Failure state of beam M2-2*

*Fig. 4(a) - Failure state of beam M5.2-1*   *Fig. 4(b) - Failure state of beam M5.2-2*

Displacement result and analysis

It can be known by comparing the displacement at the midspan section and the quartile section, the change trends of all sections are basically similar. With the deflection at the midspan section as an example, the paper introduced the deflection change in the destruction process of the test beam. The following Figure 5(a) shows the load-deflection curves of the test beam M2-1, M2-2 and the finite element model (FEM), Figure 5(b) shows the load-deflection curves of the test beam M5.2-1, M5.2-2 and the finite element model.
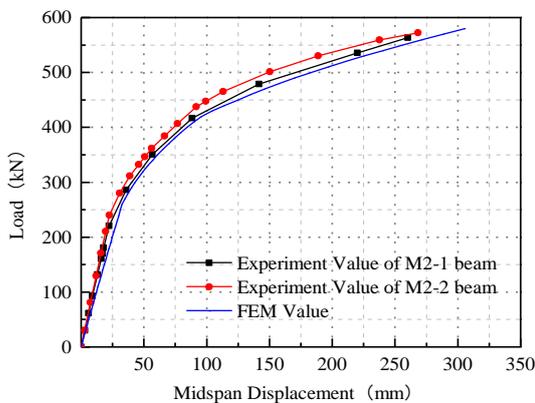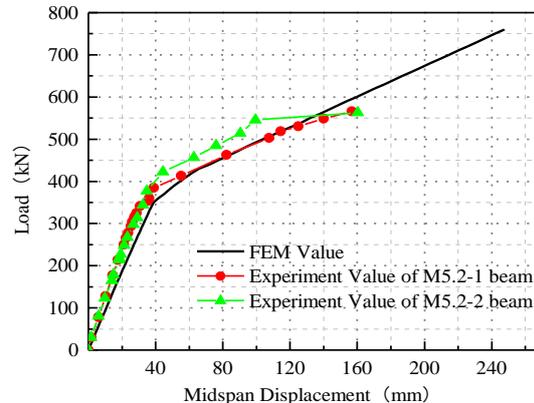
(a) M2-1 and M2-2   *(b) M5.2-1 and M5.2-2*

Fig. 5 - Load- displacement curves of midspan section of beam

It can be known from Figure 5(a) that the midspan displacements were 22.25mm and 22.57mm after the crack appeared, respectively, which are basically similar as the reversed deflection values of the test beams. As for M2-1 and M2-2 beam, the midspan deflections of the test beams were 88.43mm and 99.25mm after common reinforcement yielded, respectively, which were approximately 1/166L. The midspan deflections were 260.15mm and 268.43mm at the ultimate loads, respectively, which were approximately 1/59L. The maximum deflection obtained from the finite element model is similar as the test result of the test beam, the maximum value was 306mm. As described above, it is shown that the test beam still has excellent ductility after having served in the freezing-thawing zone for 20 years, apparent ductility anti-bending destruction features were displayed.

It can be known from Figure 5(b) that the midspan displacements were respectively 27.36mm and 26.83mm after M5.2-1 and M5.2-2 beam cracked, respectively, which are basically similar as the reversed deflection values of the test beams. As for M5.2-1 and M5.2-2 beam, the midspan

----

deflections of the test beams were 107.61mm and 99.48mm at the point of common reinforcement yielded, respectively, which were approximately 1/150L. The pre-stressed reinforcement in the bending-shearing zone slipped after reinforcement yielded, brittle destruction quickly occurred in two pieces of test beam. At the ultimate loads, the midspan deflections were 156.83mm and 160.23mm, respectively, which were approximately 1/98L. According to the calculation result in the finite element method, when the test beam was destructed, the maximum deflection value occurred in the midspan, the calculation value was 247mm. When the test beam was destructed, the maximum displacements occurred near to 5/8L, which were 166.70mm and 166.92mm, respectively. As described above, the reinforcement of the test beam had excellent ductility before common reinforcement yielded. When the pre-stressed reinforcement of the test beam slipped, not only was the structural bearing capacity lowered, but also the destruction location of structure was changed.

Stress results and analysis

The following Figure 6(a) shows the distribution of concrete strain along beam height in the midspan section of the test beam M2-1, the following Figure 6(b) shows the distribution of concrete strain along beam height at the midspan section of the test beam M5.2-1. According to Figure 6(a) and Figure 6(b), before the structure cracked, the section of the test beam M2-1 and M5.2-1 basically conformed to the hypothesis on plane section under the action of various levels of load, the ratio between the section height of the relative compressive zone and the effective height, i.e. x/h_0 is about 0.48. After the structure cracked, the neutral axis gradually moved upwardly following the increase of load. When the test beam M2-1 was destructed, the concrete at the compressive zone was crushed, x/h_0 reduced to 0.30. The neutral axis of the midspan section moved upwardly and the speed was slowly than that of M2-1 after the test beam M5.2-1 cracked. When the test beam would be destructed, the neutral axis of the midspan section would not move upwardly again, and x/h_0 reduced to 0.37 at last.
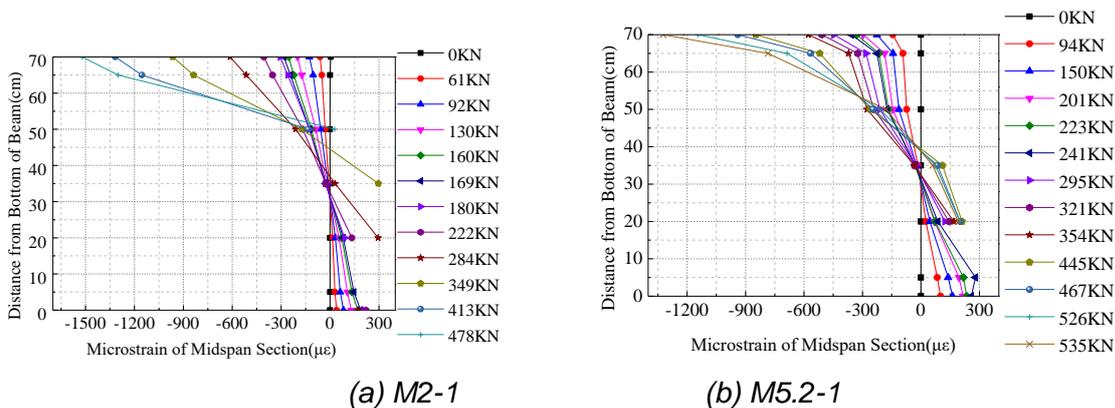

(a) M2-1   *(b) M5.2-1*

Fig. 6 - Variation of strain along cross section of beam

The following Figure 7(a) and Figure 7(b) show the curve that the concrete strain at the top edge and strain of pre-stressed reinforcement at the midspan section for the test beam M2-1 and M2-2 changes following load. It can be known that, the strain of concrete and pre-stressed reinforcement in the section linearly increased following load before the test beam cracked. When the load arrive between the cracking load and the yielding load of reinforcement, the linear increase of the strain of concrete and pre-stressed reinforcement in the section were destroyed, the increase speed of strain is higher than linear increase. After reinforcement yielded, the strain of concrete and pre-stressed reinforcement in the section quickly increased following the increase of

load. Finally, the concrete strain at the top edge of section reached the compressive ultimate strain of concrete, which lead the concrete at the top edge of section was crushed and the test beam failed.
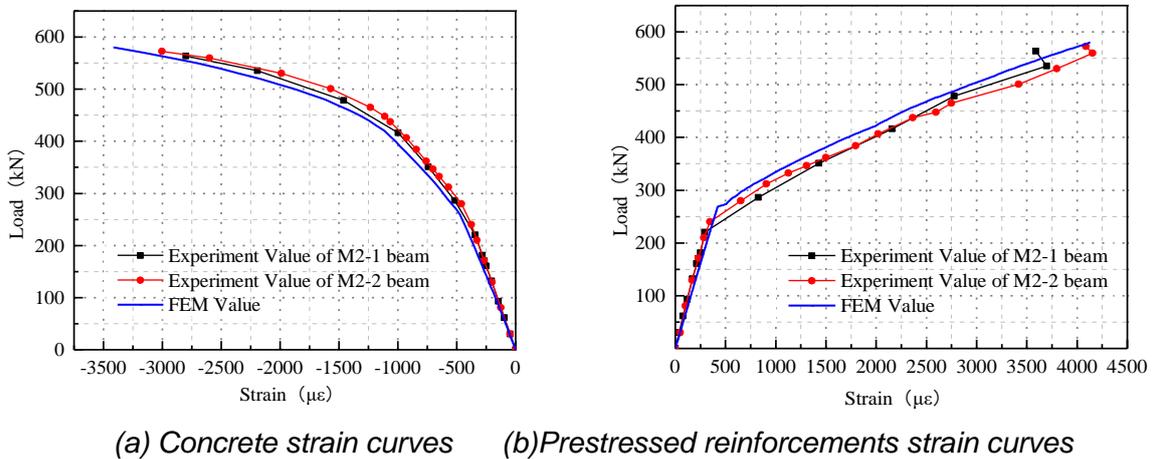

(a) Concrete strain curves   (b)Prestressed reinforcements strain curves

Fig. 7 - Load- strain curves of beam M2-1 and M2-2

The following Figure 8(a) and Figure 8(b) show the curve that the concrete strain at the top edge and strain of pre-stressed reinforcement the midspan section for the test beam M5.2-1 and M5.2-2 changes following load. It can be known that, the strain of concrete and pre-stressed reinforcement in the section linearly increased following load before the test beam cracked. When the load arrive between the cracking load and the yielding load of reinforcement, the linear increase of the strain of concrete and pre-stressed reinforcement in the section were destroyed, the increase speed of strain was higher than linear increase. After reinforcement yielded, the strain of concrete and pre-stressed reinforcement in the section quickly increased following the increase of load, but the increase speed was apparently lower than the finite element calculation value. Following the continual increase of load, the pre-stressed reinforcement in the structure slipped and the structure failed ahead of time. The concrete strain at the top edge of the midspan section do not reach the compressive ultimate strain, and concrete was not crushed.
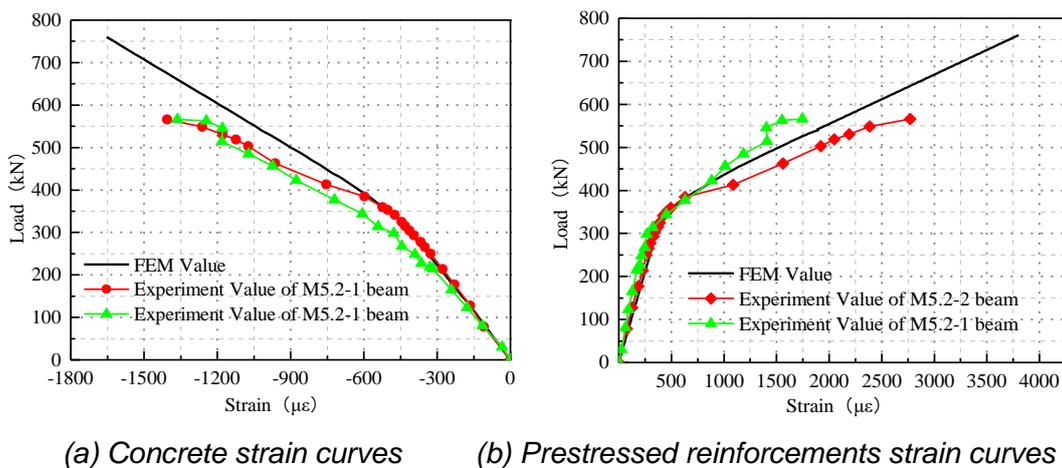

(a) Concrete strain curves   (b) Prestressed reinforcements strain curves

Fig. 8 - Load- strain curves of beam M5.2-1 and M5.2-2

Description and analysis on the cracking process of test beams

For the test beam M2-1 and M2-2, vertical crack occurred in the sagging moment zone and the crack width linearly increased following the increase of load at first stage. Oblique crack appeared in the bending-shearing zone when load continued to increase, and the growth of the crack width in the sagging moment zone decreased by a little. When the load arrive the yielding load of reinforcement, the crack height in the bending-shearing zone grew to 4/7h, the growth of oblique crack kept basically stable. At the time, the width of vertical crack in the bending moment zone quickly increased. When the crack height grew to 6/7h, the concrete at the top edge in the bending moment zone failed. Under the previous level of load before the destruction load, the average width of the crack in the test beam M2-1 was 1.35mm, the average width of the crack in the test beam M2-2 was 1.42mm. Figure 9 shows the crack distribution of the test beam M2-1 and Figure 10 shows the crack distribution of the test beam M2-2.
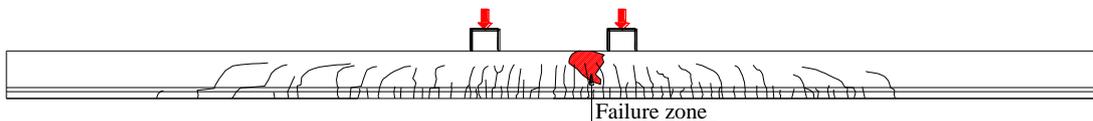

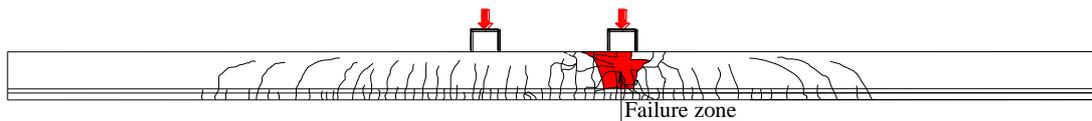*Fig. 9 - Crack distribution of beam M2-1*

Fig. 10 - Crack distribution of beam M2-2

For the test beam M5.2-1 and M5.2-2, vertical crack occurred in the sagging moment zone and the crack width linearly increased following the increase of load at first stage. Oblique crack appeared in the bending-shearing zone when load continued to increase, and the growth of the crack width in the sagging moment zone decreased by a little. When the load arrive the yielding load of reinforcement, the width and height of vertical crack in the bending moment zone grew slowly, the oblique crack developed quickly toward the direction of the loading point, its width and height developed rapidly. When load value reached the yielding load of reinforcement, the width and height of vertical crack in the bending moment zone would not grow again, the height kept stable within 4/7h~5/7h. While at this time, the width and height of oblique crack in the bending-shearing zone increased rapidly. When the height of oblique crack grew to 5/7h~6/7h, the pre-stressed reinforcement slipped, subsequently, and the width of oblique crack apparently increased. Finally, oblique crack grew to beam top at the position near to the loading point of the test beam, the concrete at beam top was crushed and such destruction belongs to bending-shearing destruction. Under the previous level of load before the destruction load, the average width of the crack in the test beam M5.2-1 was 0.89mm, the average width of the crack in the test beam M5.2-2 was 0.97mm. Figure 11 shows the crack distribution of the test beam M5.2-1 and Figure 12 shows the crack distribution of the test beam M5.2-2.
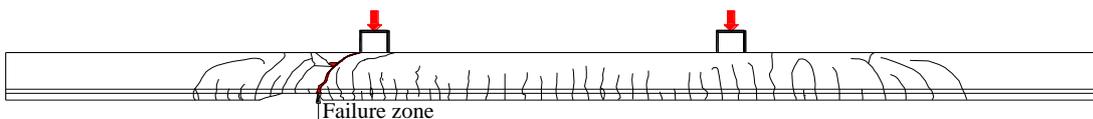

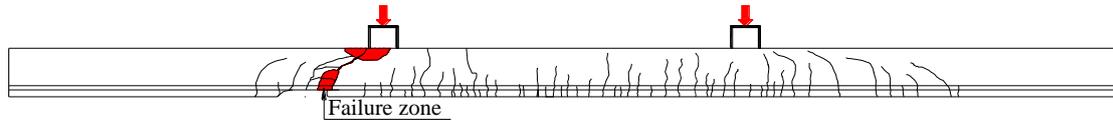*Fig. 11 - Crack distribution of beam M5.2-1*

Fig. 12 - Crack distribution of beam M5.2-2

Ultimate bearing capacity analysis of test beams

The following Table 5 shows the test results, FEM value and Eurocode value of the cracking load, yield load and ultimate load for the test beam.

Tab. 5 - Cracking load, yield load and ultimate load of test beams

Name of Test Beams	Cracking Load	FEM Value of Crack Load	Yield Load	FEM Value of Yield Load	Ultimate Load	FEM Value of Ultimate Load	Eurocode value of Ultimate Load
	(kN)	(kN)	(kN)	(kN)	(kN)	(kN)	(kN)
M2-1	221	260	416.5	420	563	580	300
M2-2	240		447.6		572		
M5.2-1	315	340	518.3	550	565.7	758	392
M5.2-2	298		545.1		565.9		

It can be known from the Table 5 that the test results of the cracking load, yield load and ultimate load for the test beam M2-1 and M2-2 are approximate to FEM value. In addition, the destruction process of these two pieces of test beam are consistent, and the average values of the test results of two pieces of beam are compared with FEM values, the ratio between the test results of the cracking load and FEM value is 0.89, the ratio between the test results of the yield load and FEM value is 1.03, the ratio between the test results of the ultimate load and FEM value is 0.98. By the comparison between the test results of the test beam M2-1 and M2-2 and FEM value, it shows that the anti-bending performance of structure decreases by a little after the structure has served in the freezing-thawing region for 20 years. As for the test beam M5.2-1 and M5.2-2, test results of cracking load and yield load of are approximate to FEM value, and the test results of ultimate load are different from the FEM value. The average values of the test values of two pieces of beam are compared with FEM values, the ratio between the test results of the cracking load and FEM value is 0.90, the ratio between the test results of the yield load and FEM value is 0.97, the ratio between the test results of the ultimate load and FEM value is 0.75. By the comparison between the test values of the test beam M5.2-1 and M5.2-2 and FEM value, it can be known that, under the action of uniform load, the test beam performed well before reinforcement yielded. The comparison between the test results and the calculated values of the Eurocode showed that the test results are much larger than the Eurocode value of ultimate load, and it is safe to adopt standard methods in structural design. However, the slip of the pre-stressed reinforcement of the test beam seriously affected the ultimate load of the structure, in the design of the pre-tensioned beam, the influence of the pre-stressed slip shall be reconsidered, especially in freezing-thawing region.

CONCLUSION

By carrying out loading test for 4 pieces of pre-tensioned pre-stressed concrete beam that have served for 20 years in the freezing-thawing region, the following conclusions were obtained:

(1)   By the test on the material strength, the detection on the durability indices of material and the appearance state of the test beams, it can be known that the pre-stressed concrete plate beam shown an excellent durability after having served for 20 years in the freezing-thawing region.

(2)   The concrete crushing at the top edge of the bending zone is taken as the destruction mark for the test beams M2-1 and M2-2. Typical ductility bending destruction occurred under the bending loading according to the responses of the tested beams including deflection, concrete strain and reinforcement strain.

(3)   M5.2-1 and M5.2-2 were adopted for the exertion of uniform load, and test results showed typical bending response features before reinforcement yielded. After this stage, the pre-stressed reinforcement in the bending-shearing zone slipped. Finally, atypical shearing-compression destruction occurred near to the loading point, such destruction belongs to brittle failure.

(4)   Finite element method was adopted to simulate the loading response of the test beam, the ratio between the average ultimate bearing capacity of M2-1 and M2-2 (567.5kN) and FEM value (580kN) is 0.98, which verifies that the bending bearing capacity of the test beam decreases by a little after having served in the freezing-thawing region for many years. The ratio between the average ultimate bearing capacity of M5.2-1 and M5.2-2 (565.8kN) and FEM value (758kN) is 0.75, which verifies that the slippage of the pre-stressed reinforcement of the test beam affected the limit of the bearing capacity of the component. In the design of pre-tensioned pre-stressed concrete beam, the influence of the slippage caused by pre-stressed reinforcement shall be considered.

REFERENCES

[1]   Jorgenson J L, Larson W.(1976), 'Field testing of a reinforced concrete highway bridge to collapse', Transportation Research Record, No.607, pp.66-80.

[2]   Shenoy C V, Frantz G C.(1991), 'Structural Tests of 27-Vear-Oid Prestressed Concrete Bridge Beams', Pci Journal, Vol.36, No.2, pp.80-90.

[3]   Azizinamini A, Boothby T E, Shekar Y.(1993), 'Old concrete slab bridges. I: Experimental investigation', Journal of Structural Engineering, Vol.120, No.11, pp.3284-3304.

[4]   Miller R A, Aktan A E, Shahrooz B M.(1994), 'Destructive Testing of Decommissioned Concrete Slab Bridge', Journal of Structural Engineering, Vol.120, No.7, pp.2176-2198.

[5]   Aktan A E, Lee K L, Naghavi R, et al.(1994), 'Destructive testing of two 80-year-old truss bridges', Transportation Research Record, No.1460, pp.62-72.

[6]   Quan Y, Teng Y, Zhu Y. (1994), 'Experimental Research on Flexural Behavior of a Deteriorated RC Bridge Under Ultimate Loading', Journal of Southwest Jiaotong University, Vol.29, No.4, pp.423-428.

[7]   Azizinamini A, Keeler B J, Rohde J, et al.(1996), 'Application of a New Nondestructive Evaluation Technique to a 25-Year-Old Prestressed Concrete Girder', Pci Journal, Vol.41, No.3, pp.82-95.

[8]   Halsey J T, Miller R. (1996), 'Destructive Testing of Two Forty-Year-Old Prestressed Concrete Bridge Beams', Pci Journal, Vol.41, No.5, pp.84-93.

[9]   Pessiki S, Kaczinski M, Wescott H H. (1996), 'Evaluation of Effective Prestress Force in 28-Year-Old Prestressed Concrete Bridge Beams', Pci Journal, Vol.41, No.6, pp.78-89.

[10] Halsey J T, Miller R. (1996), 'Destructive Testing of Two Forty-Year-Old Prestressed Concrete Bridge Beams', Pci Journal, Vol.41, No.5, pp.84-93.

[11] Harries K A. (2009), 'Structural Testing of Prestressed Concrete Girders from the Lake View Drive Bridge',

----

Journal of Bridge Engineering, Vol.14, No.2, pp.78-92.

[12] Melchers R E, Pape T M.(2013), 'Performance of 45-year-old corroded prestressed concrete beams' Proceedings of the Institution of Civil Engineers-structures and Buildings, Vol.166, No.10, pp.547-559.

[13] Olaszek P, Łagoda M, Casas J R. (2014), 'Diagnostic load testing and assessment of existing bridges: examples of application', Structure & Infrastructure Engineering, Vol.10, No.6, pp.834-842.

[14] Yuan Aimin, Sha Yangfeng, He Yu, et al. (2015), 'Experimental studies on the ultimate flexural capacity for prestressed concrete hollow beams with longitudinal cracks in webs', China Civil Engineering Journal, No.48(S1) pp.22-28.

[15] Xiang Y Q, Xiang Z, Jian Z, et al. (2015), 'Full-Range Analysis and Experimental Study of Flexural Behavior of PC Hollow Slab Beams out of Service', Bridge Construction, Vol.45, No.5, pp.30-35.

[16] National Meteorological Information Center, China Meteorological Administration. China meteorological data sharing service system. [2015-07-15].http://cdc.cma.gov.cn/index. jsp.

[17] JTJ D62-2004, Code for design of highway reinforced concrete and prestressed concrete bridges and culverts, China Ministry of Communications: Beijing, China, 2004.

[18] JTG/TJ21-2011, Specification for inspection and evaluation of load-bearing capacity of highway bridges, China Ministry of Communications: Beijing, China, 2011.

[19] Zhu L, Nie J G, Li F X, et al. (2015), 'Simplified analysis method accounting for shear-lag effect of steel-concrete composite decks', Journal of Constructional Steel Research, Vol.115, No.7, pp.62-80.