BEHAVIOR OF RC T-BEAMS STRENGTHENED WITH STEEL PLATE

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Abstract

Numerous researches on retrofitted RC beams by means of steel plate or FRP glued on tension side of the beam have been repeatedly reported cause of the economical benefit gain from strengthening an older structure instead of replacement. For the same reason, a lab experiment on strengthened RC T-beam using steel plate has been conducted and Finite Element models were also developed using commercial FE software. A T-beam section was used to represent T-beam bridge superstructure of Indonesian Bina Marga standard. Three RC T-beams were tested and each long simply supported beam was used as control beam (BC), strengthened beam (BS), and pre-cracked strengthened beam (BCS). Steel plate was used to strengthen beam BS and BCS. Deflection, crack number and crack length were measured during the test at loading increment and rate of 1 kN and 1 kN/minute, respectively. For the FE model, solid element was used for the beam, glue, and steel plate, meanwhile frame element was used for the embedded steel reinforcement. Comparison was made between the three beams in term of load-deflection relationship and flexural strength.

Keywords: RC T-Beam, Bridge, retrofit, Steel Plate, FEM

Abstak

Beberapa penelitian mengenai perkuatan balok beton bertulang dengan menggunakan pelat baja maupun dengan FRP yang ditempelkan pada bagian tarik dari balok sudah banyak dilaporkan berkaitan dengan alasan ekonomis dimana perkuatan lebih menguntungkan daripada penggantian. Untuk alasan yang sama, maka dilakukanpercobaan laboratorium dari balok T beton bertulang yang diperkuat dengan pelat baja dan juga analisa elemen hingga dengan menggunakan perangkat lunak metode elemen hingga yang banyak ditemukan di pasaran. Profil balok T digunakan untuk mempresentasikan balok T jembatan sesuai dengan standar dari Bina Marga. Tiga model balok T beton bertulang ditest dan setiap bentang digunakan sebagai control beam (BC), strengthened beam (BS), dan pre-cracked strengthened beam (BCS). Pelat baja juga digunakan untuk memperkuatn balok BS dan BCS. Lendutan, jumlah retak dan panjang retak diukur selama percobaan dengan pertambahan gaya adalah 1 kN dan peningkan sebesar 1 kN/menit. Untuk model elemen hingga, elemen solid digunakan untuk balok, lem dan pelat baja, sementara itu elemen portal digunakan untuk penambahan perkuatan baja. Perbandingan dilakukan pada tiga balok tersebut dalam betuk relasi gaya-lendutan dan kekuatan lentur.

Kata kunci: Balok T, Jembatan, perkuatan, Pelat baja, Metode Elemen Hingga

1. INTRODUCTION

The external strengthening method for reinforced concrete, RC T-beam of bridges can be applied by means of glued FRP or steel plate on tension side of beam using epoxy resin. The main advantages of the technique are simple and easy to apply without any traffic interruption. In Indonesia, there are many T-beam bridges built for the past few decades because it is the most cost effective type for short bridge with span length up to 25 meters. In the near future, the bridges need repairing, strengthening,

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or replacement due to ages, overly loaded, up-grading of road class, and exposure to weather and corrosive environment, which reduce its serviceability and strength. Considering optimum use of budget, strengthening method is preferable to replacement or building new bridges. Therefore, the strengthening efforts for RC T-beam using glued FRP or steel plate is worth investigated. In this study, steel plate is used for external reinforcement because it is readily available and less expensive. To prevent corrosion problem, the plate can be coated with thin layer of epoxy resin.

The external strengthening method can be better applied to T-beam instead of rectangular section, because it has larger compression area to balance the tension force as a result of adding external steel plates. Therefore, the strengthened beam will not reach balance condition, or overly reinforced. The steel plate as external reinforcement is designed based on available guidelines to have more effective and efficient results. To study the effectiveness of the method on deformational behavior of RC T-beams, laboratory experiment is necessary to better understand the flexure behavior of plated beams of Bina Marga standard T-beam with 15 meters span length. Finite Element (FE) models were also developed to be compared to the experimental results, to make extrapolation of test results possible.

1.1 Significance of Research

The need for retrofitting existing RC T-beams for bridges is due to the fact that there are many RC T-beams built for highway bridges of span up to 25 meters. The addition of steel plate by gluing it to tension side of beam will considerably increases the stiffness and flexural strength of the beam. The increased stiffness will reduces the deflection and increases the crack load of the beam. Therefore, application of this concept for retrofitting an existing bridge would extend the service life as well as improve the load carrying capacity of the beam. Accordingly, a significant saving on budget can be obtained because the method is simple, inexpensive, and free of traffic interruption. The research also tries to investigate the effectiveness of the method applied to pre-cracked T-beam that simulates application of the method for existing bridges with cracked beams. Therefore, application of the method will give significant flexibility of bridge budgeting.

1.2 Background

Strengthening of RC beam structures in situ by bonding steel plates to concrete surfaces using epoxy resins is now recognized to be an effective and convenient method of improving their performance under service loads or to increase their ultimate strength. The development of epoxy resins in the 1960s has made possible the strengthening of existing structures by the adhesive bonding of external steel plates to the surface members. The use of externally bonded steel plates as a means to rehabilitate reinforced concrete members was first reported in 1964, when malleable steel plates with an adhesive bond were applied to load bearing beams in the basement of an apartment building, in Durbain, South Africa (McKeena and Erki, 1994). Many more researches on success application of plated beam, mostly on rectangular sections, were reported. Based on laboratory findings and developed finite element program with sufficient parametric study, Ziraba et al (1994) suggested guidelines for the design of plated RC beam of rectangular cross section. In this study, however, the guideline is used with few modifications for T-beam with compression steel.

2. EXPERIMENTAL PROGRAM

In the experimental program, three 1/4 scaled RC T-beams were cast and tested at Structure Laboratory of Department of Civil Engineering, Faculty of Engineering, University of Udayana. The first beam is used for control (BC), the second one is strengthened with steel plate (BS), and the third beam is pre-loaded until cracked prior to strengthening (BCS). All the T-beams have the same dimensions and reinforcement which is directly scaled from the prototype T-beam of Bina Marga standard. More detail on experimental programs is as follows.

2.1 Prototype T-Beam

In this experiment, T-beam of Bina Marga standard for 15 meters span length is arbitrarily selected as prototype beam, as part of a bridge with 9.92 meter width, consisting of two traffic lane and pedestrian measuring 7 meter and 1 meter, respectively. The T-beam bridge of BM 100 classifications has six main girders of total depth 1050 mm with flange of 1700 mm wide and 200 mm thick, and web thickness of 450 mm. The T-beams are reinforced in tension with 22 D1" (25.4 mm) bars at mid span and 8 D1" bars near the supports. The compression steel used is 10 D1" bars near the supports and 8 D1" at mid span. The beams also have side reinforcement of 2 D1/2" (12.7 mm) with vertical shear reinforcement of D3/8" (9.5 mm) with 200 mm spacing and diagonal steel of 16 D1". The characteristic concrete strength is K225 or 225 kg/cm2, equal to 18.31 MPa, with steel yield strength of 2400 kg/cm2 or U24 equal to 235.3 MPa. The steel plate for external reinforcement is designed based on available guidelines proposed by Ziraba in which the reinforcement area is limited to keep the beam under-reinforced.

2.2 Design of Steel Plate

The design of steel plate is carried out according to "the guidelines toward the design of RC beams with external steel plates" proposed by Ziraba et al. (Ziraba et al., 1994). The design is done in three stages. The first step of design is to ensure that the plate and internal steel reinforcement yield to obtain ductile failure. In the second step, the interface peak stresses at the location of plate curtailment are computed and compared to the allowable values to check on status of plate debonding. In the final stage, the shear capacity of the plated beam is to be evaluated to ensure the beam does not fail in shear.

In this study, the dimension of steel plate is designed based on the dimension of scaled prototype T-beam, in which a plate of 2400 mm long, 92.5 mm wide, and 1.6 mm thick is utilized. The designated steel plate together with embedded steel reinforcement gives steel ratio of 0.69 of the ratio at balanced condition; consist of 416.65 mm^2 internal steel and 148 mm^2 plate.

Earlier studies showed that the thickness of steel plate, characteristic of adhesive, and the length of plate cut-off point from the supports, affected the mode of failure of RC plated beams. In this study, steel plate with cut-off length of 675 mm is used that gives interface peak stress at plate cut-off point less than the allowable coefficient of cohesion of 2.68 MPa. Thus, plate debonding can be avoided. The ductility and flexural failure of the beam are also functions of width to thickness ratio of steel plate (b/t) to provide small bond stress at the plate-glue-concrete interface. Such ratio must not be less than 50 (Swamy et al., 1987). In this experiment, a ratio of 57.8 was used, thus the steel plate dimension satisfied the requirements.

2.3 Model T-Beam

The model T-beam was designed as a direct strength model, where similar materials were designed for both prototype and model structures (Sabnis et al., 1983). A length scale factor of 1/4 was used to minimize the cost and to fit the laboratory conditions. As a result, the dimension of model T-beam is 3750 mm long with flange of 425 x 50 mm and web of 112.5 x 212.5 mm. The reinforcement is 5 D10.3 mm in tension and 2 D6.5 mm in compression with vertical and diagonal shear reinforcement of D4.5 at 200 mm spacing and 2 D6.5 at 280 mm spacing. The steel plate used is 2400 mm x 92.5 mm x 1.6 mm with glue thickness of 1.0 mm. The tension and compression steel for the model beams have yield stress of 410 MPa and 463.7 MPa, respectively, and the steel plate used for external reinforcement is mild steel with yield stress of 240 MPa.

The plate is glued to the bottom side of beam using epoxy resin in which the gluing process was done without turning over the beam, so that it represent the actual process in the field. For this purpose, the plate was supported temporarily until the glue hardened (Figure 4). To maintain thickness of the glue, spacers were used and moderate pressure was applied to the plate until the excess glue overflows. This process is to ensure constant thickness of glue.

In this study, the micro concrete was designed to have the same properties as that of the prototype by modeling its design compressive strength of 27.15 MPa. Natural gravel (pea gravel) with maximum size of 10 mm was used for the coarse aggregate. For the fine aggregate, however, regular sand was used to avoid a large proportion of fines that require more absorption water. Using a water cement ratio of 0.65, the final mix proportion by weight is 1:2.87:4.31 (cement: fine aggregate: coarse aggregate). The model beams were cured by covering the beams with wet materials until the age of 21 days.

No attempt was made to scale the weight of the structure because the density of the constituent materials affects the properties of the concrete. In addition, the dead load induced stress and deflection in short span bridge is small compared to the live load effects. Furthermore, similar studies on deck slab showed that incorporating dead load compensation to take into account the dead load effect did not change the behavior of the structure significantly (Hewitt, 1972).

2.4 Instrumentation and Testing

In the testing program, the truck load was modeled as two point loads simulating the middle and rear axle loads of magnitude 100 kN and ignoring the front axle load of 25 kN. This ignorance is due to limited available loading device and, if it is included in the test, the effect to maximum bending moment is relatively small (5,7% of maximum bending moment). The maximum load applied on T-beams was 1,3 times truck load considering dynamic load allowance of 0.3. The 130 kN load was then scaled to 8.125 kN for each point load to be applied on rubber loading pads measuring 50x125 mm. Figure 1 shows the experimental set up and cross section of model T-beam.

Loading and unloading of the beams were done at an increment and rate of 1 kN and 1 kN/minute, respectively. Prior to loading, the steel plate was glued to the beam BS. The BS and the other two beams were than tested with 10 cycles of loading to have more data on load-deformation relationship. After 10 loading cycles, the third beams, BCS was strengthened with steel plate and then 5 more loading cycles were applied. After testing the beams to maximum service load level, then they were tested to failure. In each loading cycle, after maximum load of 16.25 kN, the load was gradually released until zero value indicated on the meter. The deflections at midspan are measured using dial gauges. In addition, the crack measurements include length, spacing, and width, were taken regularly during loading and unloading process up to maximum service load and during loading up to failure. The crack width was measured using crack detector with accuracy up to 0.01 mm.

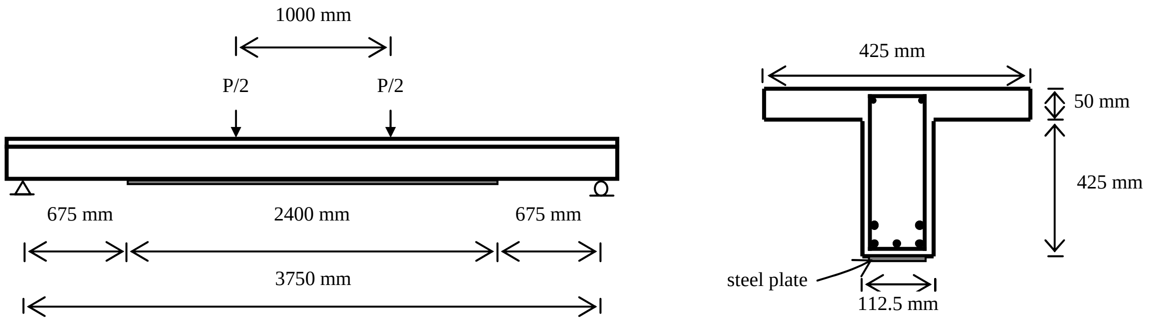

Figure 1. Experimental set up and cross section of model T-beam

2.5 FE Modeling

Finite Element modeling of T-beam was conducted using commercially available software, SAP2000 version 9.0 to mimic the behavior of beams with and without steel plate under service load. The purpose of FE model is to obtain numerical solution of the problem to be compared to the test result. Once the solution available, no physical test is necessary but computer models, as long as the numerical solution is reliable. The other advantages gained from the FE model is faster, cheaper, and more convenient to do. In this study, the T-beams, glue, and steel plate were modeled using solid elements and the embedded steel reinforcements were modeled as frame elements. Non-linear static analyses were performed to obtain load-deflection relationship of the T-Beams. Two loads of 8.125 kN were applied on two areas measuring 50x125 mm.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Testing of T-beams was started after the model beams cured at 28 days. The average compressive strength of model concrete was 27.72 MPa which is higher than the target strength of 27.15 MPa. However, the difference is not important as comparison is made within the same concrete strength. The corresponding test results are as follows.

3.1 Deflection of T-Beam under Service Load

Under maximum service load in the first loading cycle, the control beam (BC) deflect as much as 3.6 mm, and when the load was released back to zero there was permanent (residual) deflection of 1.2 mm caused by reduced stiffness of cracked beam. At following loading cycles, the maximum load of 16.25 kN produced varying maximum deflections between 3.8 mm and 4.1 mm with the same value of residual deflection. The average value of maximum deflection is 4.0 mm. The complete graph of load-deflection relationship for BC is shown in Figure2 (left).

It is apparent from the graph that the control beam shows elastic behavior under service load. In addition, the cracks developed under service load were small and they are totally recovered (closed) upon unloading. The next loading cycle did not cause any additional crack, in agreement with constant stiffness of the beam. The permissible deflection of T-Beam for bridge is L/800 which corresponds to 19 mm. The measured value of 40 mm in ¼ scale beam is equal to 16 mm in prototype beam, which is still smaller than the permissible value.

T-Beam strengthened with steel plate (BS) behaved in similar manner to BC with smaller deflection value. Figure 2 (right) shows the load-deflection relationship for the strengthened beam. The first loading cycle produced maximum deflection of 1.7 mm with residual value of 0.3 mm. The next cycle of loading did not change the behavior of beam, in agreement with zero crack development.

The third T-Beam which was pre-loaded (pre-cracked) prior to strengthening (BCS) behaved just like BC until steel plate was added. With additional steel plate the BCS was reloaded for the 11th until 15th loading cycles. Figure 3 (left) shows the load-deflection relationship for the pre-cracked strengthened beam (after steel plate addition) under service loading. The first loading cycle, before strengthening, produced maximum deflection of 3.6 mm with residual value of 1.3 mm. The maximum value after strengthening is 13.8% less than that before strengthening. Interestingly enough, the next loading cycle after strengthening (12th until 15th) did not cause additional deflection and crack in the beam. This is a proof that, with steel plate addition, the cracked beam becomes significantly stiffer and stronger.

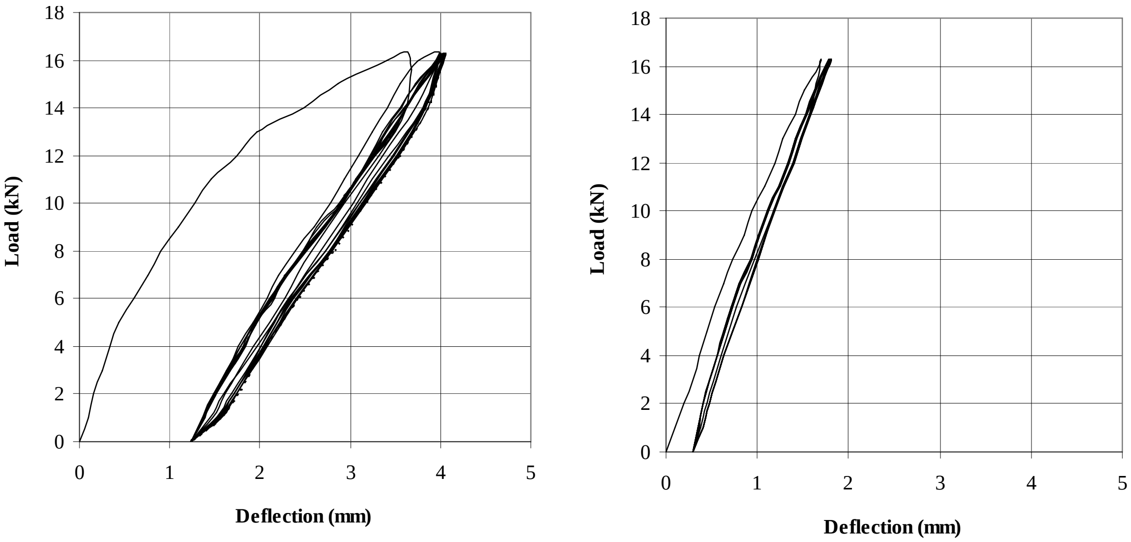

Figure 2. Load-deflection relationship of Control Beam, BC (left) and Strengthen Beam, BS (right)

3.2 Crack of T-Beam under Service Load

Crack development under service load is important measure for the effect of adding steel plate on the beams. Visible first crack in control beam developed under the point loads of total magnitude about 11 kN. These cracks were followed by similar cracks developed from the load points toward mid span. The theoretical crack load is 11.3 kN in which maximum tensile stress in the beam exceeds concrete modulus of rupture of 3.65 MPa. At a load of 16.25 kN the maximum height of crack was measured 185 mm, about 87% of the height of web, with maximum crack width of 0.08 mm. The crack height did not increase in the following load cycles but its width increase up to 0.1 mm. The crack spacing varied between 30 to 100 mm with higher crack density between load points. The cracks developed during second loading cycle were recovered upon unloading with crack width remain the same. The next loading cycle did not cause any additional crack, in agreement with constant load-deflection relationship as shown in Figure 2.

The strengthened beams, BS performed much better than the control beam in which, compared to that for control beam, the number and height of cracks in BS were about 20% and 50%, respectively. In the pre-cracked strengthened beam, BCS there was no crack growth recorded after strengthening which means that the additional steel plate is capable of stopping the crack growth. The detail of crack pattern and height of strengthened beam, BS is shown in Figure 4.

3.3 Test Result Under Ultimate Load

Beam behavior under ultimate load was also of interest pertaining to the effect of additional steel plate on the RC T-beam. Such behavior was measured after 15 cycles of loading under service load. The control T-beam, BC failed at maximum load of 56 kN which is 6.7% more than the predicted ultimate value of 52.48 kN. Considering maximum service load value of 16.25 kN, safety factor of 3.4 is obtained for the control beam.

The strengthened T-beam, BS failed at a load of 68 kN which is 7.57% higher than the theoretically predicted value of 63.21 kN. The pre-cracked T-beam had the same ultimate strength as that of BS because of the same internal steel reinforcement and external steel plate used for both beams. Figure 3 (right) shows the graph of load-deflection relationship of the three beams loaded up to failure. As expected, the addition of steel plate as external bending reinforcement in beams BS and BCS increases the flexural strength of the beam as much as 21.4%. Also can be seen from the graph that at failure load of 56 kN for the control beam, the deflection of strengthened beam BS and BCS are significantly smaller than that of control beam, they are 36.4% and 42.7%, respectively.

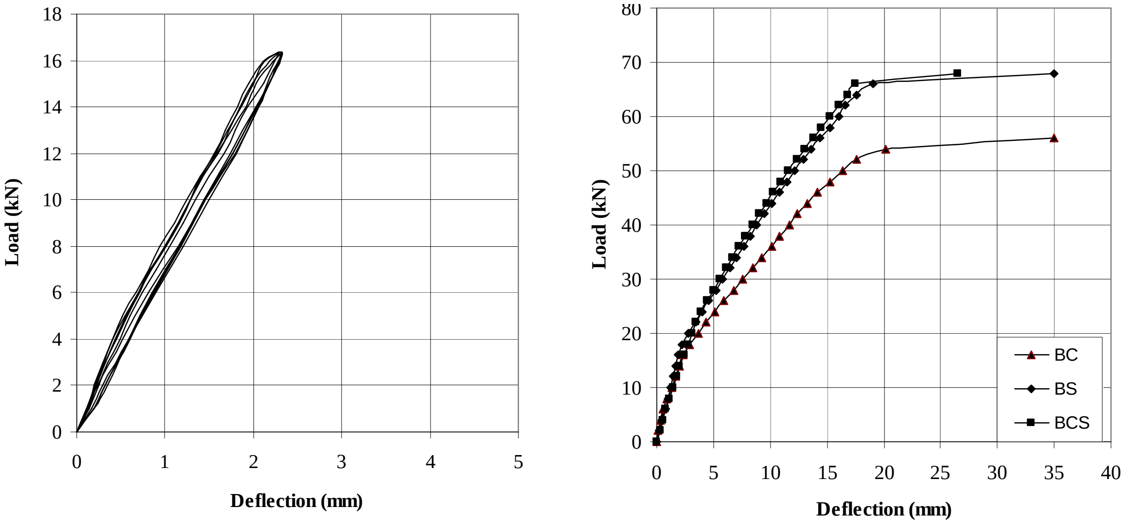

Figure 3. Load-deflection relationship: BCS under service load (left), all beams under ultimate load (right)

Failure mode of all beams is also the same which is flexural failure as noted by wide cracks develop along the portion of beams with maximum bending moment. There was no sign of debonding failure between concrete and steel plate which indicates that the steel plate design, based on design guidelines proposed by Ziraba et al. (Ziraba et al., 1994) performs satisfactorily.

Figure 4. Installation of steel plate from underneath (left) and crack detail of beam at failure (right)

3.4 Finite Element Models Compared to Test Result

The results from Finite Element models are plotted in Figure 5 together with test result from lab. The graph shows that FE model for the control beam, BC give stiffer responses than the test result, while for the strengthened beam, BS the test result is slightly stiffer than the result from FE model. It is apparent, however, that the load-deflection relationship of the strengthened beams under service load is well predicted in FE model with maximum difference of about 4%. However, the FE models fail to mimic the load-deflection relationship of the cracked control beam. Therefore, the FE prediction could be used for strengthened RC T-beam more accurately than that of control beam.

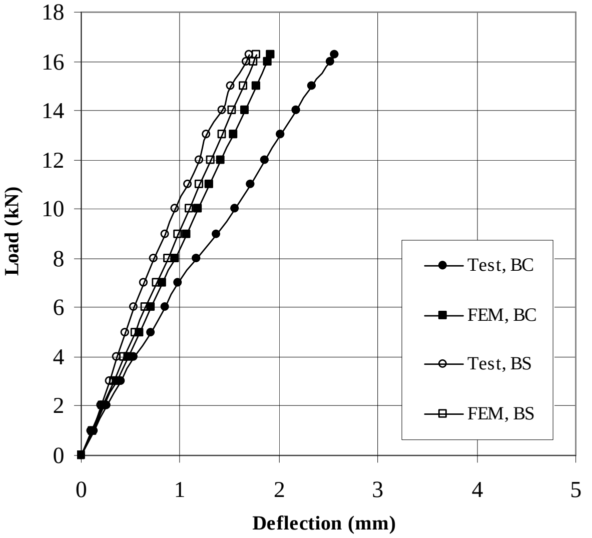

Figure 5. Load-deflection relationship of BC and BS, test and FE models

4. CONCLUSION AND RECOMENDATION

Based on test results and Finite Element models, it can be concluded that the addition of steel plate glued on tension side of RC T-Beam is effective in increasing the stiffness of the beam as well as reducing the number, width, and height of cracks developed in the beam. The external reinforcement also significantly increases the flexural strength of the beam. Compared to the control beam, BC the ultimate strength of strengthened beams, BS and BCS are 21.4% higher. In addition, under service load, the stiffness of BS and BCS is 55% and 9.9% higher than that for BC. The beam with external steel plate reduce the crack number up to 80% with crack width and height 41.7% and 52.6% lower than those of control beam. Load-deflection relationship of the strengthened beams under service load is well predicted in FE model with difference of 4%. However, the FE models fail to mimic the load-deflection relationship of the cracked control beam.

This study suggest that the strengthening method using glued steel plate is applicable for RC T-Beam for bridges because it is inexpensive and easy to apply in the field without any traffic interruption. The strengthening design can utilize FE model because of its close response to the test results. Further research is necessary to obtain stress, strain, and crack development in the beam for different size of steel plate and glue thickness. Utilization of FE software that incorporates post crack properties of RC is recommended.

5. ACKNOWLEDGEMENTS

This research has been possible with supports from Department of Civil Engineering at University of Udayana. Special thanks are due to colleagues at the department for their input and comments during various stages of the experimental program.

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