External strengthening of reinforced concrete beams with strand without stressing under flexural loading

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Abstract. This research was purposed to study the composite behavior and the increased capacity of reinforced concrete beam strength under flexural loading caused by external strand without stressing. The specimen is divided into 2 types. Type-I specimen has (150 x 300 x 3200) mm dimension with center point loading, and distance of strand clamp as (Ubars) variable; whereas, the Type-II specimen has (200 x 300 x 3200) mm dimension with third point loading, and the number of strand as variable. The test is carried out by static-monotonic loading, and displacement control. Experimental test results shows that the addition of strand on the lower surface of the beam increase the beam's load capacity. However, the use of U-bars affects the stability of the concrete. The tighter distance of the U-bars decrease the capacity of the strengthening occurred. The increased load capacity of Type I specimens, S3-150, S5-150 and S9-150 are 33.2%, 17%, and 12.1% against control beam (BK-150), respectively. Whereas, the increased capacity of the type-II beam strength of test specimens B1-200 and B2-200 are 10% and 17% against control beam (BN-200), respectively. And the increase of initial stiffness of beam Type-I test specimen S3-150, S5-150, and S9-150 are 14%, 18% and 5% against control beam (BK-150), respectively. Meanwhile, the increase of initial stiffness of Type-II beam of test specimens B1-200 and B2-200 are 21% and 24% against control beam (BN-200), respectively. This study shows that concrete and strand bonding is not compatible. The concrete has been reaching the limit strain, as well as the steel reinforcement in the concrete has been in yielded; meanwhile, strand that has fy is much higher than fy of reinforced steel, is still in elastic condition.

1. Introduction
The rapid growth and development of economic establishment and technology in the last decades has led to volume and load increment of heavy vehicle on roads and bridges in Indonesia; thus, constructed roads and bridges mostly receive exceed vehicle’s load from the design load. Along with an increase of need for traffic on roads and bridges infrastructure, it is also expected to increase strength, safety, and comfortability.

The preferred strengthening element method of flexural structure is by utilizing FRP (Fiber Reinforced Polymer). However, this method relatively inquires high cost. Whereas, jacketing strengthening method resulted in increased building weight. Besides, retrofitting using stressing strand requires extra scrutiny of the location of an anchor (difficulty of installation) [1]. Based on the several reinforcement alternatives, retrofitting using strand can increase significant capacity strength, since strand has high yield stress and small volume [2]. Research on strengthening of prestressed concrete by
stressing have been conducted. However, such strengthening is complicated implementation, because it requires extra supervision when doing stressing. So, the research on strand strengthening without stressing is needed.

The requirement of the composite structure between the reinforced concrete beam and the external strand strengthening is the compatibility between them. Therefore, the beam with a composite strengthening must be able to work as a monolithic composite structure element. Beam with composite strengthening can work as a monolithic composite beam if the strain on a concrete beam with the strand is equal. To achieve the monolithic composite state is predicted to be done by using the gluing and anchoring method [3].

2. Methods

The specimens were divided into 2 (two) types that are described in Table 1. Test method of Type I specimens based on ASTM C293-02 center-point load, displacement control state, while the test method for Type-II specimens based on ASTM-C78 three-point monotonic, displacement control.

| No | Specimens Code | Longitudinal Bars | Confinement Bars | Cover Concrete (mm) | The Number of Strands | U-Bars | Anchor Method |
|----|----------------|------------------|-----------------|-------------------|----------------------|-------|---------------|
|    |                | Position | Bar at I-End (Momen-) | Bar at J-End (Momen-) | Bar at I-End (Momen-) | Bar at J-End (Momen+) | Distance (mm) |
| 1  | BK-150         | Top Bars | 2D13 | 2D13 | 2D13 | 2D13 |
|    |                | Bottom Bars | 2D13 | 2D13 | 2D13 | 2D13 |
| 2  | S3-150         | Top Bars | 2D13 | 2D13 | 2D13 | 2D13 |
|    |                | Bottom Bars | 2D13 | 2D13 | 2D13 | 2D13 |
| 3  | S5-150         | Top Bars | 2D13 | 2D13 | 2D13 | 2D13 |
|    |                | Bottom Bars | 2D13 | 2D13 | 2D13 | 2D13 |
| 4  | S9-150         | Top Bars | 2D13 | 2D13 | 2D13 | 2D13 |
|    |                | Bottom Bars | 2D13 | 2D13 | 2D13 | 2D13 |
| 5  | BN-200         | Top Bars | 4D13 | 2D13 | 4D13 | 2D13 |
|    |                | Bottom Bars | 2D13 | 2D13 | 4D13 | 2D13 |
| 6  | B1-200         | Top Bars | 4D13 | 2D13 | 4D13 | 2D13 |
|    |                | Bottom Bars | 2D13 | 2D13 | 4D13 | 2D13 |
| 7  | B2-200         | Top Bars | 4D13 | 2D13 | 4D13 | 2D13 |
|    |                | Bottom Bars | 2D13 | 2D13 | 4D13 | 2D13 |

Illustration of Type I test design for reinforced concrete beams strengthening by strand is shown in the Figure 1. Strand is attached to the underside of the beam by gluing using epoxy, then the strand is clamped with U-bars steel with distance variations of 750 mm, 375 mm and 187.5 mm implanted into.

While the Type-II test specimen, reinforced concrete beam strengthening by is shown in Figure 2. At both ends the strand is carried out by using a steel plate. The strand is attached by gluing with epoxy, then the strand is clamped with U-bars at a distance of 200 mm (this follows the tests conducted by Demir and Tekin [4]) which are stretched into the beam and attached using epoxy.
Figure 1. Type I specimens with strengthening.

Figure 2. Type II specimens with strengthening.

Figure 3. Control test specimen (a) Type I and (b) Type II.
Strain gauges were installed on steel reinforcement and strands to observe strain; while, the deflection of the concrete beam was measured through LVDT. The strain gauges and LVDT positions can be shown in Figure 4 and Figure 5.

![Figure 4. Strain gauge and LVDT positions on Type-I specimens.](image)

![Figure 5. Strain gauge and LVDT positions on Type II test specimens.](image)

2.1. Testing set up

Testing set up, as shown in Figure 6 and Figure 7, the specimen is put on the loading frame with the roll-pin restraint condition at both ends [5]. In the Type-I specimen, the loading was carried out at the center of the beam span or at 1500 mm from the restraint. Meanwhile, the Type II specimen, the loading was done on 1/3 span of reinforced concrete beam at 1000 mm from the restraint.

![Figure 6. Set up of type I specimen.](image)

![Figure 7. Set up of type II specimen.](image)
3. Test results

3.1. Load-displacement relationship

The result of the loading test is shown in load displacement curves. The curve shows the value of first crack load (Pcr) and maximum load (Pmax). Figure 8 shows the result test of Type-I specimens. The curves have the same behavior between the composite strand strengthening beams and the control beam (BK-150). It shows that adding a strand compositely on the bottom surface of the reinforced concrete beam increased the load capacity. As shown in the figure 8, with the same displacement, specimen S3-150 produced the highest maximum load, 40.632 kN; whereas, the test specimens S5-150 and S9-150, respectively were 35.689 N and 34.188 kN. In other words, the addition of strand increased the load capacity by 33.2%, 16.9% and 12.1% respectively to the BK-150 control beam (30.504 kN).

![Figure 8. The load-displacement curve of Type I specimens.](image)

The test result of Type-II specimens is shown in Figure 9. As shown in the figure, the load vs displacement curve at the elastic condition had the same behavior between the composite strand strengthening beam and the control beam.

The maximum load of BN-200, B1-200 and B2-200 are 71.557 kN, 78.418 kN and 83.552 kN, respectively. The results show that maximum load of composite strand strengthening beam higher than control beam.

![Figure 9. Load-displacement curve Type-II specimens.](image)

Load-displacement curves also show stiffness behavior of the beams during loading tests. The addition of strand as strengthening on the bottom surface of the concrete beam could increase the stiffness of the beam. The results show that, addition of 1 strand on Type I specimens increase the stiffness of S3-150, S5-150 and S9-150 test specimens against control beam by 14%, 18% and 5%, respectively. However, on specimens S9-150, U bars at distance of 187.5 mm (the closest distance), there was a decrease in
stiffness. The U bars embedded in the concrete affected the stability of the concrete beam, so that the more closely the bars of the U used, the smaller result of stiffness value and vice versa. Thus, in the use of U-bars should be done restrictions. In this research, the depth of U-bars reinforced concrete was not taken into account, so further studies are needed to determine the depth or length of the U-bars as a strand clamp. The value of the first crack load and the maximum load for each beam, as well as the stiffness value occurring, are listed in Table 2.

### Table 2. Stiffness value of type I specimens.

| Specimen | First Crack | Displacement 98 mm |
|----------|-------------|--------------------|
|          | $P_{cr}$ | $\delta_{cr}$ | Stiffness | $P_{mm}$ | $\delta_{mm}$ | Percent ($P_{mm}$) |
|          | kN/mm | mm | kN/mm | % | kN | mm | % |
| BK-150   | 15.75 | 7.53 | 2.09 | 0 | 30.50 | 98 | 0 |
| S3-150   | 18.83 | 7.89 | 2.38 | 14 | 40.63 | 98 | 33.2 |
| S5-150   | 18.26 | 7.39 | 2.47 | 18 | 35.68 | 98 | 17 |
| S9-150   | 17.15 | 7.82 | 2.19 | 5 | 34.18 | 98 | 12.1 |

As well as the Type I Specimens, the Type II test specimen stiffness analysis was performed during the initial stiffness condition (stiffness in the first crack condition). The first crack in the B1-200 beam decreased when compared to the control test object (BN-200). The cause of this decrease was due to the decrease in cross section of the beam. U-bars (strand clamps) used on Type-II test specimens at 200 mm apart and added with anchoring into the concrete so that the cross-sectional area is reduced more than the Type I test specimens. The large number of cross sectional area reductions due to the U-bars led to a decrease in the first crack load; whereas, strengthening by adding 2 (two) strands (B2-200) may increase the first crack load by 6% against the control beam (BN-200) and increase the first crack loading by 19% due to the influence of the U-bars on the specimen B1-200.

### Table 3. Stiffness value of type II specimens.

| Specimen | First Crack | Maximum Load |
|----------|-------------|--------------|
|          | $P_{cr}$ | $\delta_{cr}$ | Stiffness | $P_{mm}$ | $\delta_{mm}$ | Percent ($P_{mm}$) |
|          | kN/mm | mm | kN/mm | % | kN | mm | % |
| BN-200   | 44.32 | 16.46 | 2.69 | 0 | 71.55 | 86.04 | 0 |
| B1-200   | 39.44 | 12.15 | 3.24 | 21 | 78.41 | 67.68 | 10 |
| S9-150   | 14.12 | 14.12 | 3.32 | 24 | 83.55 | 71.17 | 17 |

The stiffness analysis of the Type II test specimens showed that the addition of strand can increase the stiffness of test specimens B1-200 and B2-200 to control beam (BN-200) by 21% and 24%, respectively. Meanwhile, the maximum load increased of test objects B1-200 and B2-200 to control beam (BN-200) is 10% and 17%, respectively. Understandably, the difference in the addition of the strand amount gives rise to the stiffness and maximum load value that occurs. However, the increase in the number of strand was not significantly different in stiffness value on test specimens B1-200 (1 strand) with B2-200 (2 strand) only differ 3% while the maximum load that happened was different 7%.

### 3.2. Pattern of collapse

#### 3.2.1. Type-I specimen test. From the observation of the crack pattern, the control test specimen (BK-150) cracked pattern that occurred in the form of flexural crack and some flexural-shear cracks (the 1/3 spans of middle area). The collapse occurred on the BK-150 specimen began with a crack in the tensile zone under load $P$ and increase in the region which had great moment, the first crack occured. As the
given load increased, the crack got longer and wider and new cracks occurred in 2/3 spans (1000 mm left-right load). With the addition of the load would cause the increase crack pointing upward toward the neutral line of the beam (there is the flexural collapse occurred). And when the load was increased to 76% of the maximum load, the crack direction that occurred tends to form a angle of 45º or more to the beam axis (a shear failure occurred). The collapse of shear-flexural occurred due to the strength of the concrete and the tensile strengthening and the shear strengthening was not sufficient to withstand the value of the load occurred.

Figure 10. Crack pattern of BK-150 specimen.

Meanwhile, the result of the composite strand strengthening beam specimen observation on crack pattern that occurred was in the form of flexural crack (1/3 spans area of center of load) and dominant shear crack (2/3 spans of load). The collapse occurred was begun with the sound of ruptures in the epoxy lining the strand at the end (the direction of the roll restraint) and the middle of the strand span. Epoxy ruptures then epoxy that attached the strand to the concrete surface slightly apart. The epoxy strand started to detach at the end of the strand in the direction of the roll, then followed by the middle (under loading area). Epoxy was released with a width of ± 1 mm, gradually enlarging in the area. There is a difference in load between the rollers and joints during the process of removing the epoxy. First, the end of the strand in the direction of the roll restraint started to release and followed by the middle (area under load). Due to the epoxy was not applied evenly to the entire surface of the strand during the installation of the reinforcing material, so that the first release of the epoxy is only the end of the strand in the direction of the roll. Simultaneously there was a crack in the layer of concrete blanket, and it increase relatively perpendicular to the neutral line, the first crack occurred.

As the load increased, the epoxy ruptures louder and there was crack in the epoxy then debonding occurred between the strand and the concrete surface. After the specimens cracked on the epoxy or the strand strengthening adhesive, and as the load increases, it showed that the epoxy which is a strand adhesive with concrete loosed gradually until the strand has debonding between strand and concrete. As illustrated in Figure 11 and Figure 12.

Figure 11. Debonding between strand and concrete at the end of the beam.
Simultaneously when debonding occurred the crack width is significantly larger and longer, and new cracks emerged. Then when the load was increased to 71% (S3-150), 66% (S5-150) and 55% (S9-150) of the maximum load, the test specimen had a shear crack at 2/3 span of the source load position (1000 mm) and some diagonal oblique cracks which were a continuation of prior flexural cracks in the 1/3 spans or 500 mm left to right of the load, were flexural-shear cracks. The addition of a strand on the bottom surface of a concrete beam was taped with epoxy and clamped using a U-bars to make the strand did not only increase the pliable capacity as designed. Strand mounted externally on the concrete surface and stretched with U-bars into concrete, to affect the stability of the concrete. As the load increases, the U-bars affected the result of collapse in a shear crack. According to the observation of crack pattern that occurred at strengthening specimen S9-150, it tends to have more cracks than previous strengthening test S3-150 and S5-150. The cracks that emerge generally appeared at a radius of 50 mm from the shape of the U-bars reinforcing strand. Therefore, the U-bars caused weakness in the cross section of the beam that caused crack.
3.2.2. Type-II test specimen. According to the observation of the crack pattern, the control test object (BN-200) of the cracking pattern occurred in the form of a flexural crack in the middle of the span between the load or in the area who got a great moment and some flexural cracks in the 2/3 spans of the load against restraint. The collapse occurred in the test specimen BN-200, preceded by a crack in the tensile area between the load and developing in the 2/3 spans of the load, occurred first crack. As the load increased, the crack increased in length and width. With the addition of the load would cause the increase crack pointing upward toward the neutral line of the beam (there was a flexural collapse). And, when the load was increased up to 63% of the maximum load, the crack direction that occurred tends to form a 45º angle (shear collapse occurred). Also, the collapse of shear-flexural occurred due to the strength of the concrete and the tensile strengthening, and the shear strengthening was not sufficient to withstand the value of the load that occurred. Cracked failure pattern was seen just before the collapse.

This beam would continue to experience displacement in the absence of a load increase and the crack became more open so that the neutral line continues near to the depressed edge. Eventually it caused the destruction of the concrete. Thus, from the collapsed pattern that occurred was the flexural-shear failure.

Meanwhile, the specimen of the crack pattern that occurred, begun with the sound of rupture on the epoxy that attaches the strand to the concrete and then epoxy started to detach slightly. The first off epoxy occurred at the end of the strand area close to the position of the anchor. Moreover, the epoxy was cracked and followed by cracked layers of concrete blanket before finally the first crack of the concrete emerge (first crack). The first crack occurred in the tensile area between the load and it increase on the 2/3 span of the load source to the restraint. As the load increased, the crack length and width were increased. With the addition of the load would cause the increase crack pointing upward toward the neutral line of the beam (there was a flexural collapse). And when the load was increased to 58% (B1-200) and 66% (B2-200) of the maximum load, there was a shear crack. The flexural-shear fracture of the reinforcement specimen occurred more often than in the control test object (BN-200).
Before the maximum load occurred, the curves of load bond and displacement showed the post-serviceability crack area, where the tensile strength stress reached its yield stress. The load-bond curve with displacement is much flatter than the previous area until it reached the maximum load and eventually collapsed. When the beam collapsed marked by a decrease in the load-displacement curve, the crushing occurred in the press region or in other words, the concrete stressing in the compression area reached the limit of (ecu = 0.003), while the strengthening of the strand was assumed to be in an elastic state. Understandably, the bonds between concrete and strand are incompatible, concrete as an element of crushing structure has reached crushing, as well as strengthening that is in the concrete already in yielding condition. Meanwhile, strand that has fy much higher than fy reinforced steel strengthening, when the concrete and reinforced steel strengthening has already collapsed, strand still in elastic condition.

4. Conclusion
The conclusion of this research is as follows:

- The maximum strength capacity of reinforced concrete beams had increased with the addition of strand on the lower surface of the beam. Increased capacity of beam were 12% - 33% to beam control.
- The addition of strands on the reinforced concrete beam was able to increase the initial stiffness, 5%-24% to the control beam.
- The use of U-bars as a strand affected the stability of the concrete; so, the form U-bars needs to be restricted. This study proves that the closer the distance of bars U decreased the capacity of the beams.
- The control beams had flexural cracks and some shear cracks. Meanwhile, when the composite strand strengthening beam had the dominant shear crack. The strand mounted externally on the concrete surface and anchored with U-bars into concrete, to affect the stability of the concrete. As the load increases, the Ushape rebound affects the collapse pattern which results in a shear crack.
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