



Decreasing Strength of Prestressed Concrete Beams Due to Failure of Part of the Strands Withdrawal

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Abstract. This research paper is to study the decreasing strength of a 22,1-meter long Prestressed Concrete U Girder due to two strands in a tendon out of six tendons being unable to be stressed. This matter is a cause of an error in the implementation of the PC-U girder manufacturing, resulting in a reduction in the area of the tendon sleeve (duct); two out of seven pieces of the strand cannot be inserted thoroughly. PC-U girder performance will suffer a decrease in strength, so it needs to be checked and handled. This paper is an actual project condition and was researched to verify how much strength reduction is due to such a case. The analysis is performed to measure and compare the moment capacity of cross-sectional conditions with the results of the designed section. Moment capacity analysis is carried out to determine the ability of the cross-section to support the working load with a bonded tendon. Research methodology involves calculation of moment capacity M_u using trial and error processes of calculating the depth of neutral axis c using Equilibrium Equation so that with a trial c value, ultimate prestressed strain value ϵ_{pu} and ultimate prestresses stress value σ_{pu} coincide in the Moment- Curvature curve line. Using the overlapped c value, the Moment capacity of the girder with a whole strand can be calculated. A similar procedure is performed with a reduced strand number. The difference between the two is the reduced prestressed concrete strength. Evaluating both analyses, it is found that a decrease in the moment capacity of the cross-section is as much as 530,93 kNm to the designed moment capacity of 18,108,06 kNm or approximately 2,93% of its original designed strength.

keywords: prestressed concrete, strand, moment capacity

INTRODUCTION

The superstructure elements of Tanjung Priok Access Highway in Jakarta, Indonesia, are dominated by an elevated bridge with 60 spans made of PC-U girders 22,1 meters long for each span. Problems affect other works in the implementation of PC-U girder works. The main problem is that the cable strands cannot be inserted into the tendon sleeve for the PC-U girder type B P95-P96. The PC-U girder has six (6) tendons with two different types. There are two tendons, MA 59 07 MA, and four, MA 59 12 MA. One of the tendons with type MA 59 07 MA can only be put with five (5) cable strands, while the original design should have seven (7) strands. These two strands cannot be inserted into the tendon because the duct is bent, which causes a bottleneck condition with a smaller duct diameter in one part of the tendon. The other five tendons have no problems with strand cable insertion. This study will determine the effects of failing to insert and stressing two (2) out of 60 cable strands in the six tendons of the PC-U girder cross-section.

A flexural-sectional analysis will be carried out to study the problem above. This analysis involves strain calculations, equating internal tension and compression forces, comparing curvature to minimum curvature, processing trial, and error to obtain the depth of neutral axis c to get ultimate prestressed strain ϵ_{pu} and ultimate prestressed stress σ_{pu} , which is close enough to section moment-curvature curve line and calculating ultimate moment capacity M_u .

Flexural sectional analysis is carried out to determine the behavior of the prestressed concrete section, which can be performed before and after cracks occur. There are two cross-sectional analyses for prestressed concrete: the short-term and the long-term. The short-term analysis is usually carried out for non-cracked sections. The short-term analysis is carried out by transforming the reinforcement to an equivalent area of concrete using the Modulus Ratio Theory.

Long-term cross-sectional analysis is usually carried out for a long time and is influenced by time. Long-term analysis is carried out to accommodate the effects of shrinkage and creep, which are highly dependent on the age of the Prestressed Concrete structural components. Therefore, long-term analysis is also called time-dependent analysis. There are also two conditions concerning tendon condition, i.e., bonded and unbonded tendons, for section analysis. Considering the nature of this strand inserted into the tendon's duct, a Short-Term Analysis of the uncracked bonded tendon member will be implemented here.

RESEARCH METHODOLOGY

One of the most essential parts of the structural design of bridges is flexural strength. Introducing prestressing will give more resistance to external loads. Applying a prestressing force to any structural member will result in stresses due to direct and eccentric load combinations [1]. An interpolation method is used to evaluate the Ultimate Moment Capacity M_u . This method fits the interpolated neutral axis c value depth to ultimate prestressed strain ϵ_{pu} and ultimate prestressed stress σ_{pu} . These two ultimate stresses and strains shall be close enough to the Moment Curvature curve line of the strand used for PC U-Girder. Based on the actual structural bridge at the project, in which every tendon is grouted, the cross-section analyses are performed with bonded tendon assumptions.

The ultimate strength of the cross-section concerning bending (M_u) is calculated based on the theory of flexural strength, which involves the strength of concrete and steel in tensile and compressive fibers. This strength limit simultaneously limits the level of strength limit (strength limit states). Besides the strength of the section, it is also necessary to check its ductility. The code of practice provides for ductility requirements by limiting the ultimate curvature at a minimum value, thus ensuring significant deformation before failure occurs. In this evaluation, since the objective is to determine the decreasing value of ultimate moment capacity, ductility checks will be performed by comparing κ_u to $\kappa_{u \text{ min}}$. The basic assumption for cross-sectional analysis is to obtain the ultimate flexural strength or M_u based on the assumptions in sub-chapter 2.2. SNI 2002 stipulates that the outermost fiber's compressive strain is $\epsilon_{cu} = 0,003$. Generally, since the tensile strength of concrete is lower than its compressive strength, for design purposes, SNI 03-2874-2002 [2] stipulates the tensile strength of concrete at $\sigma_{ts} = 0,5 \sqrt{f'_c}$. It is known that the deformation of concrete is direct and time-dependent. At a constant load, the deformation increases with time. The strain development over time is mainly controlled by shrinkage and creep strain. The sum of the strains in the structure at time t is the sum of the strains. The following are equations used for determining the Moment Capacity of PC U-Girder as parts of the strand withdrawal [3].

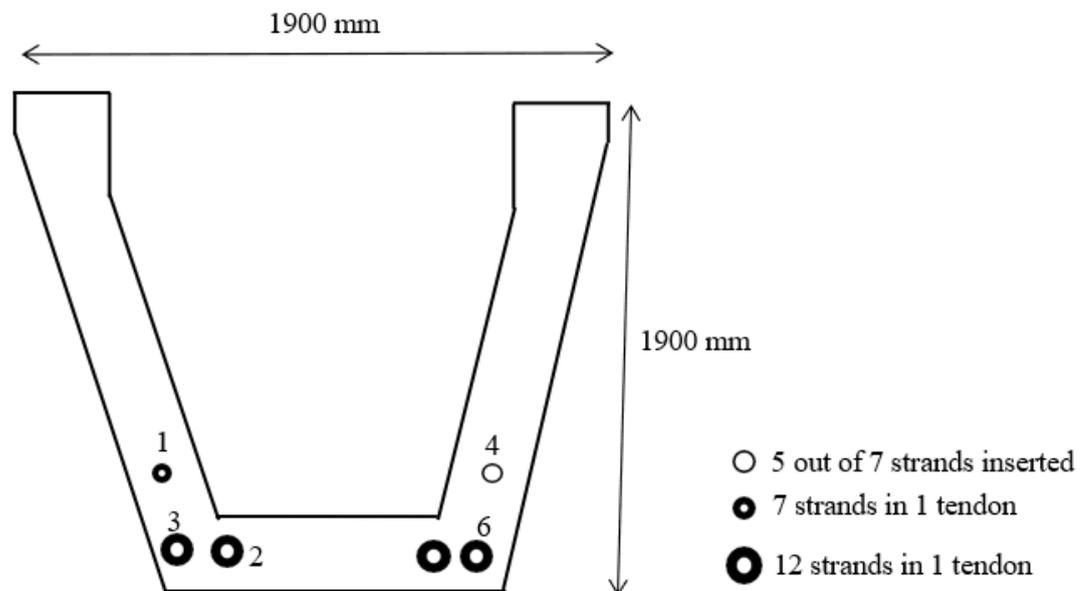
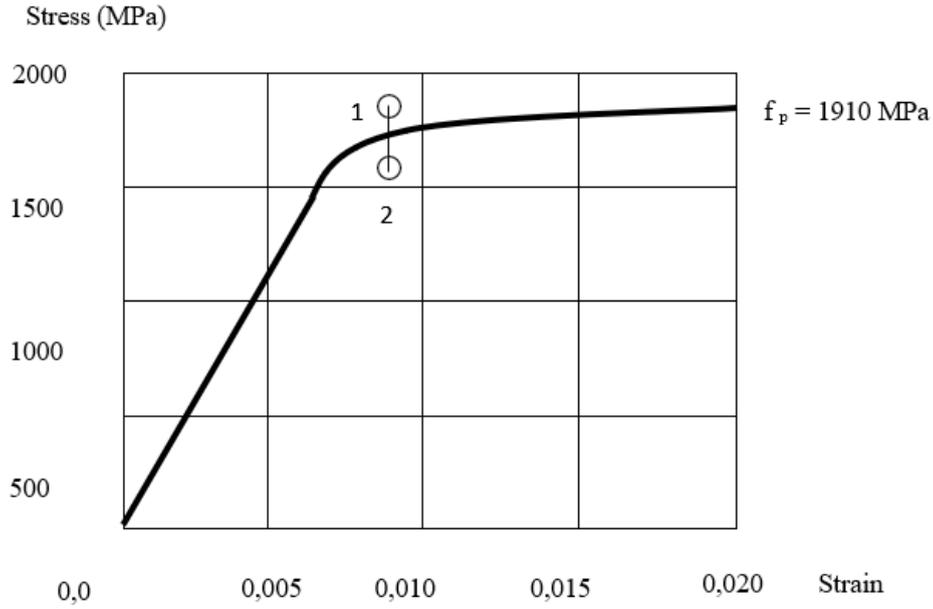


FIGURE 1. Simplified Midspan Cross Section of PC U-Girder



$$\varepsilon_{pe} = \frac{P_e}{E_p \cdot A_p} \quad [\text{Eq. 1}]$$

$$\varepsilon_{ce} = \frac{1}{E_c} \left(\frac{P_e}{A} + \frac{P_e \cdot e^2}{I} \right) \quad [\text{Eq. 2}]$$

$$\varepsilon_{pt} = \varepsilon_{cu} \left(\frac{d_p - c}{c} \right) \quad [\text{Eq. 3}]$$

$$C_l = 0,85 \cdot f'_c \cdot b \cdot \beta \cdot c \quad [\text{Eq. 4}]$$

$$T = A_p \sigma_{pu} \quad [\text{Eq. 5}]$$

$$\kappa_u = \frac{\varepsilon_{cu}}{c} = \frac{0,003}{c} \quad [\text{Eq. 6}]$$

$$\kappa_{u \text{ min}} = \frac{\varepsilon_{cu}}{0,4 d_p} = \frac{0,0075}{d_p} \quad [\text{Eq. 7}]$$

$$M_u = \sigma_{pu} \cdot A_p \left(d_p - \frac{\beta \cdot c}{2} \right) \quad [\text{Eq. 8}]$$

$$P = A_p f_p UTS \quad [\text{Eq.9}]$$

$$f_r = -\frac{P}{A} - \frac{P \cdot e}{W_b} + \frac{M_{cr}}{W_b} \quad [\text{Eq.10}]$$

The PC U-Girder, which has a section width of 1900 mm and a section height of 1850 mm, is shown in Figure 1. Checks on the tendon spacings have to fulfill corrosion, fire, and other requirements [4]. Only the midspan cross-section of PC U-Girder is evaluated to focus on the structural calculation discussion. The stress

– The strain curve of the strand used is shown in Figure 2.

The first step in research methodology is to calculate the cross-sectional area of the PC U-Girder. Using a cross-section of a structural member, stress and strain diagrams are analyzed with their assumptions made [5]. A tabulated calculation is thoroughly performed to make the inertia of the PC U-Girder's cross-section easier to calculate.

By tabulating the calculation for Section Area, the distance from the center gravity of the section to the top and bottom fiber will be found. The Moment of Inertia and Resisting Moment to the top and bottom of the section will also be calculated directly. Since the shape of the section is not uniform, it is divided into several parts, with rectangle and triangle shapes.

Equations 1, 2, and 3 can calculate the values of ϵ_{pe} , ϵ_{ce} , and ϵ_{pt} . Since the depth of neutral axis c is unknown, the calculation of c is made with c as one parameter. The value of T is also made with the parameter σ_{pu} . Setting Equilibrium $\Sigma H = 0$, then $T = C$ and the relation of σ_{pu} and c can be estimated. The next step is to proceed with the trial and error process using the trial c value, calculated ϵ_{pu} value, calculated σ_{pu} value, and plotting those values to the stress and strain curve of the strand. When the values of ϵ_{pu} and σ_{pu} coincide or are close enough to the stress and strain curve, the trial c value is considered correct. The next step is to calculate $\kappa_{u \min}$ and κ_u . If κ_u is greater than $\kappa_{u \min}$, the ductility requirement is fulfilled. Having the c and σ_{pu} values, the Ultimate Moment Capacity can be calculated using Equation 7. As formulated in Eq. 6, the curvature in the section expresses the ratio of the ultimate strain of concrete ϵ_{cu} and the depth of neutral axis c [6]. Using a stress-strain curve in the trial-and-error process is also adequate to represent the flexural behavior of the PC U-Girder under short-term load.

DISCUSSION

Facts about strands are first introduced to discuss the Failure of Part of the strand withdrawal. Strand wire (or strand) is widely used for prestressed concrete with a post-tension system. The strand used has to meet the requirements of ASTM A 416. The strand widely used is a strand of seven wires with two qualities: Grade 250 and Grade 270. The diameter of the strands varies between 7,9 and 15,2 mm. Strands' tensile stress (f_p) is between 1750 – 1860 MPa. The modulus of elasticity is $E_p = 1,95 \times 10^5$ MPa.

For design purposes, the yield stress value can be taken as 0,85 times the tensile stress ($0,85 f_{ps}$). Typical stress-strain diagrams for strands can be seen in Figure 2. In a prestressed concrete structure, all steel bars discussed above shall have been anchored to the end of the structure to ensure the prestressing force works on the girder. After discussing the strand as the main focus of this study, the evaluation of missed strand insertion is continued with PC U-Girder structural calculations.

The shape of the PC U-Girder cross section is not uniform; therefore, the section is divided into 17 parts with rectangle and triangle shapes. Adding all parts of the section, the Area of section A is 1.356.499,36 mm², equal to 1,36 m². The distances from the center of gravity to the top fiber are 950,88 mm = 0,95 m and 899,12 mm = 0,90 to the bottom fiber. Momen of Inertia I is 448.776.924.355,33 mm⁴ = 0,45 m⁴. The resisting top moment $W_a = 471.959.578,87$ mm³ = 0,47 m³. The resisting bottom moment $W_b = 499.129.064,37$ mm³ = 0,5 m³. One parameter left for calculating the section's Moment Capacity is the tendon's elongation to the girder section's center of gravity. Considering the location of four tendons and their sizes, the section elongation values vary from 140 to 1200 mm. This elongation is the distance between the center of the cross section's center of gravity and each tendon's center. The concrete quality used for PC U-Girder f'_c is 40 MPa. This face value determines $\beta = 0,77$. The Modulus Elasticities of concrete and prestressing strands are 30.000 MPa and 195.000 MPa, consecutively. All structural calculations, including the trial and error processes, are made concerning [7].

Since the PC U-Girder has six tendons, the discussion of the flexural strength is divided into three parts. The division is based on the group of tendons with the same elevation and hence the same elongation, e . They are Tendon numbers 1 and 4, 2 and 5, and 3 and 6. Every group of tendons is calculated twice for its trial and error processes. In this evaluation, because its purpose is to determine the effects of the failure of part of the strand withdrawal, all structural calculations are based on the designed and actual conditions.

Prestressing force is calculated using Eq. 8. With $A_p = 98,70$ mm² and $f_p = 1860$ Mpa, Prestressing force for tendon 1 is $P_1 = 904$ kN. Other tendons, $P_2 = 1547$ kN, $P_3 = 1558$ kN, $P_4 = 904$ kN, $P_5 = 1547$ kN, $P_6 = 1558$ kN. Prestressing force for the failing tendon $P_{4f} = 646$ kN. The total cracking moment M_{cr} is calculated using Eq. 10 with $f_r = 0,7 \sqrt{f'_c} = 4,43$ N/mm², $M_{cr} = 11.135.569.426,09$ Nmm = 11.135,57 kNm. The cracking moment for the failure of part of the strand withdrawal $M_{crf} = 10.730.775.754,89$ Nmm = 10.730,78 kNm. It is shown here that Cracking Moment M_{cr} is less than the Ultimate Moment of M_u . Crack has not taken place here. Therefore, uncracked section analysis will be performed using Elastic Theory [8].

The results for structural calculations for tendons 1 and 4, 2 and 5, and 3 and 6 are made using Eq. 1 to Eq. 10 concerning Budiadi [9]. Due to the limited number of pages for this paper, only tendon one and, similarly, tendon four are presented in the calculation to show the procedures as follows:

$$E_c = 4700\sqrt{f'_c} = 4700\sqrt{40} = 29.754,41 \text{ N/mm}^2$$

$$\beta = 0,85 - 0,008(f'_c - 30) = 0,85 - 0,008(40 - 30) = 0,77.$$

$$\varepsilon_{pe} = \frac{P_e}{E_p \cdot A_p} = \frac{903.407,02}{195.000 \times 690,90} = 0,00671$$

$$\varepsilon_{ce} = \frac{1}{E_c} \left(\frac{P_e}{A} + \frac{P_e \cdot e^2}{I} \right) = \frac{1}{29.754,41} \left(\frac{903.407,02}{1.356.499,36} + \frac{903.407,02 \times 1200}{448.776.924.355,33} \right) = 0,00012$$

$$\varepsilon_{pt} = \varepsilon_{cu} \left(\frac{d_p - c}{c} \right) = 0,003 \left(\frac{1500 - c}{c} \right)$$

$$Cl = 0,85 f'_c \cdot b \cdot \beta \cdot c = 0,85 \times 40 \times 600 \times 0,77 \times c = 15.708 c$$

$$T = A_p \cdot \sigma_{pu} = 690,90 \times \sigma_{pu}$$

$$\sum H = 0 \rightarrow T = Cl \rightarrow 690,90 \sigma_{pu} = 15.708 c \rightarrow \sigma_{pu} = \frac{15.708 c}{690,90}$$

The ε_{pu} and σ_{pu} values are calculated using trial and error methods and then plotted to the stress and strain curve. First trial using $c = 85$ mm, ε_{pt} is :

$$\varepsilon_{pt} = 0,003 \left(\frac{d_p - c}{c} \right) = 0,003 \left(\frac{1500 - 85}{85} \right) = 0,04994$$

$$Cl = 0,85 \cdot f'_c \cdot b \cdot \beta \cdot c = 0,85 \times 40 \times 600 \times 0,77 \times 85 = 1.335.180,00$$

$$T = A_p \cdot \sigma_{pu} = 690,90 \sigma_{pu}$$

$$\sum H = 0 \rightarrow T = Cl \rightarrow 690,90 \sigma_{pu} = 1.335.180,00 \rightarrow \sigma_{pu} = \frac{1.335.180,00}{690,90} = 1932,52 \text{ N/mm}^2$$

$$\varepsilon_{pt} = \varepsilon_{pe} + \varepsilon_{ce} + \varepsilon_{pt} = 0,00671 + 0,00012 + 0,04994 = 0,05677 \approx 5,68\%$$

Second trial and error is performed with a value equal to 75 mm and end up with $\varepsilon_{pt} = 6,38\%$.

Connecting the coordinates of ε_{pu} and σ_{pu} for the first and second trials by a line until they intersect with the Moment Curvature diagram in Figure 2, a c value is calculated to have $c = 81,81$ mm.

$$\varepsilon_{pt} = 0,003 \left(\frac{d_p - c}{c} \right) = 0,003 \left(\frac{1500 - 81,81}{81,81} \right) = 0,05201$$

$$Cl = 0,85 f'_c \cdot b \cdot \beta \cdot c = 0,85 \times 40 \times 600 \times 0,77 \times 81,81 = 1.285.071,48$$

$$T = A_p \cdot \sigma_{pu} = 690,90 \sigma_{pu}$$

$$\sum H = 0 \rightarrow T = Cl \rightarrow 690,90 \sigma_{pu} = 1.285.071,48 \rightarrow \sigma_{pu} = \frac{1.285.071,48}{690,90} = 1.860,00 \text{ N/mm}^2$$

$$\varepsilon_{pu} = \varepsilon_{pe} + \varepsilon_{ce} + \varepsilon_{pt} = 0,00671 + 0,00012 + 0,05201 = 0,05884 \approx 5,88\%$$

TABLE 1. Calculating resume

C (mm)	ε_{pu} (%)	σ_{pu} (MPa)	Point
85	5,68	1.932,52	1
75	6,38	1705,17	2
81,81	5,88	1860,00	*

$$\kappa_u = \frac{\varepsilon_{cu}}{c} = \frac{0,003}{81,81} = 3,7 \times 10^{-5} \geq \kappa_{u \min} = \frac{0,0075}{d_p} = \frac{0,0075}{1500} = 5 \times 10^{-6} \rightarrow OK$$

$$M_u = \sigma_{pu} \cdot A_p \left(d_p - \frac{\beta \cdot c}{2} \right) = 1860 \times 690,90 \times \left(1500 - \frac{0,77 \times 81,81}{2} \right) = 1887,14 \text{ kNm}$$

For tendons 2 and 5, the first trial with $c = 150$ mm, $\varepsilon_{pu} = 0,0377$, and $\sigma_{pu} = 1989,36$ MPa. The second trial with $c = 130$ mm, $\varepsilon_{pu} = 0,0429$ and $\sigma_{pu} = 1724,11$ MPa. They connect the coordinates of ε_{pu} and σ_{pu} for the first trial and second trial by a line until they intersect with the Moment Curvature diagram; a c value is found to have $c = 139,42$ mm. With this, c values ε_{pu} and σ_{pu} are calculated, and the results are 0,0402 and 1.849,05 MPa consecutively. After checking that κ_u is greater than $\kappa_{u \min}$, the Ultimate Moment Capacity for tendons 2 and 5 is 3.583,57 kNm.

For tendons 3 and 6, the first trial with $c = 150$ mm, $\varepsilon_{pu} = 0,0376$, and $\sigma_{pu} = 1989,36$ MPa. The second trial with $c = 130$ mm, $\varepsilon_{pu} = 0,0428$ and $\sigma_{pu} = 1724,11$ MPa. They connect the coordinates of ε_{pu} and σ_{pu} for the first and second trials by a line until they intersect with the Moment Curvature diagram; a c value is acquitted of having $c = 139,40$ mm. With this, c values ε_{pu} and σ_{pu} are calculated, and the results are 0,0402 and 1.848,78 MPa, respectively. After checking whether κ_u is greater than $\kappa_{u \min}$, the Ultimate Moment Capacity for tendons 1 and 4 is 3.584,07 kNm. Adding all Ultimate Moment Capacity with all strands inserted $M_u = 18.108,06$ kNm.

When failure of part of the strand withdrawal occurs, the structural calculation is only performed for tendon numbers 1 and 4. The other four tendons have the same calculations. Since the number of strands differs, tendons 1 and 4 are calculated separately. Tendon 1 has seven wire strands, while tendon 4 has 5. For tendon 1, after the first and second trials, the calculated $c = 81,81$ mm. The Ultimate Moment Capacity for tendon 1 is 1887,14 kNm. For tendon 4 with the first trial, $c = 62$ mm, and the values of ε_{pu} and σ_{pu} are 0,0764 and 1.973,45 MPa, respectively. In the second trial, $c = 50$ mm, the values of ε_{pu} and σ_{pu} are 0,0938 and 1.591,49 MPa, respectively.

The calculated c is 58,44 mm. After checking that κ_u is greater than $\kappa_{u \min}$, the Ultimate Moment Capacity for tendon 4 is 1356,21 kNm. Hence, the total Ultimate Moment Capacity for this condition is 17.577,13 kNm.

CONCLUSION

Due to prestressing forces, beam self-weight, and external loads, the stress component of prestressed concrete is usually calculated using the assumption that the material's behavior is linear-elastic. The property of the cross-section does not have cracks. This is the main reason why most Codes of Practices such as SNI 03-2874-2002 [2], ACI 318-83 [10], and AS 3600-1988 [11] prefer to implement uncracked section elastic analysis rather than cracked one. British Standard and European code BS 8110-1985 [12] and CEB-FIP [13] also implement uncracked sections for structural analysis. Although concrete does not behave linearly, linear elastic calculations can accurately estimate the stress in the section immediately after the load is applied. According to the working load design concept, this working stress must be less than the allowable stress of the material.

The PC U-Girder bridge is designed using a simple span structure throughout the Tanjung Priok Access Highway. The girders are loaded using RSNI T-02-2005 [14] and designed RSNI T-12-2004 [15] using designated strands to comply with ASTM A416-74 [16]. Such a simple span structure needs to experience the structural complexity of a continuous structure. However, as a prestressed concrete member where the tendon shall have anchorages at the end of the PC U-Girder, anchorage design can follow any anchorage design. Simple span beam structural design is mainly dominated by flexural strength design. Other designs like shear and torsion have little influence on the design calculations. Shear strength for box girder type beam has adequate strength by its two webs. So, shear is refined by designing a box girder-type bridge. The box girder has an advantage in the torsion due to its boxy type. This advantage is used by a bridge designer to resist torsion load due to nonsymmetrical geometry or loads.

Nevertheless, the structural design and the site problem shall be evaluated to get the project done and the problem solved. The decreasing strength of prestressed concrete beams due to the failure of part of the strand withdrawal has concluded its problem. Knowing the strength decreases, a solution can be proposed to cope with the situation. The ultimate moment capacity for all strands inserted to all six tendons $M_u = 18.108,06$ kNm. Due to the Failure of Part of the Strands Withdrawal in tendon 4, the ultimate moment capacity is 17.577,13 kNm. Thus, the Failure of Part of the Strands Withdrawal in Tendon 4 is the difference between the both. Calculating the difference is as much as 2,93% of its original design. Knowing the decreasing strength, recalculating the ultimate moment capacity against the external moment due to traffic and other loads is the next to consider.

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