A Numerical Study on the Control of Horizontal Cracking at the Ends of BS22 Hollow-type PC-girders Utilizing Midas FEA

Abdul Khaliq KARIMI$^{1,2}$*, Bashir Ahmad AASIM$^{1,2}$ and Jun TOMIYAMA$^3$

$^1$PhD candidate, Department of Civil Engineering and Architecture, University of the Ryukyus, Okinawa, Japan
$^2$Civil Engineering Department, Kandahar University, Kandahar, Afghanistan
$^3$Professor, Department of Civil Engineering and Architecture, University of the Ryukyus, Okinawa, Japan

*Karimi@kdru.edu.af

Abstract. When the prestressing forces transfer from PC-strands to concrete, a region of stress concentration develops at the ends of pretensioned girders, which often results in horizontal cracking during or just after the detensioning process. In this study, a hollow PC-girder was modeled utilizing a Finite Element Analysis software Midas FEA to identify the horizontal cracking locations in terms of the principal stresses at the end-zone of the hollow PC-girder. Strand-debonding and placing end-zone reinforcements were hired in this work by introducing four cases. The only strand-debonding method could not prevent horizontal end crack penetration. Though the end-zone reinforcements were placed alongside the strand-debonding, this combination could reduce principal stresses to a level that could bring the crack size to a negligible range.

1. Introduction
Pretensioned PC-girders became famous in the civil engineering field because of longer distances and high load-carrying capacity [1]. Some research has observed that prestressed girders show horizontal cracking at their ends due to prestressing forces [2]. Horizontal cracks occur during or just after the prestress releasing; these cracks are visible when lifting the girder from prestressing bed. The problem can severely affect the structure if the crack pattern results in paths leading to corrosion of embedded steel bars. However, the cracks can be sealed and may be acceptable if the width is smaller and does not pose durability concerns [3].

After transferring prestressing forces to concrete, compressive stresses develop and propagate into the girder in a curved manner from the ends and get a linear distribution beyond the transfer length, as shown in figure 1. The required bond length for PC-strands to fully transfer prestressing forces to concrete is called the transfer length [4]. As a result of the bonding effects, compressive stresses develop and act radially in the direction of the strands; their dispersion causes tensile stresses, which act normal to the prestressing strands [5]. Horizontal cracks occur at the girder ends when the magnitude of these tensile stresses, called principal stresses, becomes more than the concrete tensile strength.
Figure 1 The spreading of bond-stresses into a PC-girder [6].

Figure 2 Horizontal cracks occurred at the end of a real hollow PC-girder.

Horizontal end cracks are observed at the ends of various shapes girders, such as box girders, I-shaped girders, hollow slabs, and tee beams [7]. Researchers conducted different studies to control horizontal cracks at the ends of the mentioned types of girders. However, there is little research on hollow-type girders, whereas they are vulnerable to horizontal end crack development due to the large prestressing forces. Actual horizontal cracks at the end of a real hollow PC-girder are shown in figure 2.

Hollow girders are an excellent alternate for bridge construction as they produce highly lightweight and consume significantly less material. Hollow girders have holes along the length, but they express an excellent load-bearing capacity to vertical loadings.

The purpose of this study was to suppress or at least minimize horizontal cracking at the ends of the pretensioned hollow PC-girders. The BS22 hollow girder is quite vulnerable to horizontal cracking due to its great height (900 mm) and many tendons (22 PC-strands) used in the girder. This girder demands a vast amount of prestressing forces that generate horizontal cracks at the girder's ends; thus, the BS22 hollow girder was selected for this study. BS represents the B-live load slab girder, and the number illustrates the span length of the girder. In this work, MIDAS FEA software was chosen as the Finite Element Analysis (FEA) tool to create the girder models and investigate the horizontal end crack condition.

2. Numerical analysis
Nonlinear FEA was used to examine the horizontal crack situation at the girder's ends. In this study, steel reinforcements and concrete performance were investigated at the ends of the BS22 hollow girder during prestressing and just after the strand-releasing process. The relationship between horizontal cracking and stresses or strains which causing them is also discussed in this work. Furthermore, factors that are causing to increase in the strains are also discussed. As the girder's geometry and loadings are symmetric, one-fourth of the girder was modeled and shown in figure 3.
The strands used in this modeling are having a 15.2 mm diameter, and the transfer length for these strands was calculated as 988 mm according to the JRA standards [8]. Based on a parametric analysis [9], bond stress and the threshold value of slipping were selected as 5.0 N/mm² and 0.2 mm, respectively. The selected girder for this work represents the horizontal cracking problem during or after strand-release. The achieved results of this study are applicable for all similar girders.

### 2.1. BS22 girder normal model

The normal BS22 girder was modeled in this case to find that where horizontal cracks are likely to occur. After all the prestressing forces were transferred to concrete, the magnitudes of principal stresses in the girder end zone's concrete were as shown in figure 4.

Figure 4 shows that the principal stresses at the girder's end are more than the tensile strength of concrete; thus, horizontal end cracks are likely to occur in this case. However, the magnitude of principal stresses is not the same throughout the girder's height; just in a portion of the height (400 mm to 470 mm), principal stresses are more significant than the tensile strength of concrete, and horizontal cracks occur in that portion only.

**Figure 3** Isometric view and half cross-section of BS22 girder model.

**Figure 4.** Principal stress variations at the girder end with all fully bonded strands. (Case 1).
2.2. BS22 model with debonding four strands

Strand-debonding is one of the methods used here to reduce principal stresses. The idea is to delay the stress transfer between prestressing strands and concrete due to bonding; since the stress transfer between strands and concrete starts further into the concrete element, the end regions' stresses are reduced. In this model, four PC-strands were debonded for a distance equal to the transfer length at the girder's end. The magnitude of principal stresses in the vertical edge of the girder end from this model was as shown in figure 5. The principal stresses at the girder end in this model were less than those developed in the previous model; however, they are still greater than the concrete tensile strength, and the possibility of horizontal cracking was not eliminated by employing only the strand-debonding method.

![Figure 5. Principal variations at the end of BS22 girder with four debonded strands (Case 2).](image)

2.3. Modelling of BS22 girder with end-zone reinforcements

2.3.1. End-zone reinforcement design. Placing end-zone reinforcements is another method used in this study to further reduce principal stresses at the girder’s ends. Researchers propose a procedure to design end-zone reinforcements [10]; according to their proposed design technique, the required steel area of end-reinforcements was computed using the following equation,

\[
A_s = 0.4 \times A_{ps}
\]  

(1)

In this equation, \(A_{ps}\) is the total area of prestressing steel, equal to 3051.4 mm\(^2\) for the BS22 girder. The required Total steel area calculated from Eq. (1) was equal to 1220.56 mm\(^2\). The selected type of rebar used in the modeling was as end-reinforcement was D10 or steel bars with 10 mm diameter; this bar's cross-sectional area is equal to 78.5 mm\(^2\). The obtained quantity of stirrups required to be positioned at the girder end was equal to 16 bars. Researchers [10] recommend putting at least 50% of the achieved steel area inside a distance (h/8) from each end of the girder. On the other hand, it seems complicated to set 8 stirrups inside 112.5 mm length; the problem that arises is the spacings between stirrups which will be less than the minimum required spacings. For that reason, the designed steel bars were arranged as a mesh, and it is referred to as the end-mesh. End-mesh is shown in figure 6. 

![End-mesh](image)
2.3.2. **Principal stresses.** The designed end-mesh was modeled in Midas FEA and placed in the girder model 40 mm distant from the end; principal stresses at the ends of this model are shown in figure 7. The magnitude of principal stresses in figure 7 is also more than the concrete tensile strength, and horizontal cracks are likely to occur in this case as well. Thus, it can be said that only strand-debonding or placing end-zone reinforcements alone cannot eliminate horizontal cracking at the BS22 girder ends. Therefore, in this study's next model, end zone reinforcement and strand-debonding were used simultaneously in the BS22 girder model to eliminate horizontal end cracking.

![Figure 7](image_url)

**Figure 7.** Principal stress variations at the girder end with an end-mesh placement. (Case 3).

2.4 **BS22 model with placing end-mesh and debonding four strands.**

In this model, an end-mesh of D10 bars was placed at the girder’s end, positioned 40 mm far away from the end. Additionally, four PC strands were debonded in the lower horizontal row. The aim was to check the strand-debonding and end-zone reinforcements combined effects on the reduction of principal stresses. The magnitude of principal stresses from this model is shown in figure 8. Effective stresses of concrete at the centreline of the bottom fiber are shown in figure 9.
Figure 8. Principal stresses at the girder end with end-mesh and four debonded strands. (Case 4).

Figure 9. Effective stresses of concrete at the centreline of bottom fibre.

Figure 8 shows that, in most portions of the girder height, principal stresses are less than the concrete tensile strength; however, they are still more than the concrete tensile strength in few points; yet these principal stresses are very close to the concrete tensile strength. These stresses can create horizontal cracks; nevertheless, the crack width will be minimal and within the acceptable range. JRA specification for concrete bridges [8] suggests the acceptable crack width as follows: “if the crack width is less than 0.3 mm, these cracks are acceptable, and they will not damage the structural capacity and durability concerns of the concrete member, only cracks could be sealed to avoid the ingress of chlorides”.

3. Conclusion
The following conclusions are provided based on the numerical studies performed in this research:
• Horizontal end cracks occur in the typical BS22 hollow girder after transferring all prestressing forces to concrete.
• The width of horizontal end cracks and their number can be reduced significantly by strand-debonding.
• The most effective reinforcement strategy to control end-zone horizontal cracks is to place the reinforcing bars at the girder's very end. Organizing the designed rebars as a mesh shape is an excellent solution to arrange the required end-reinforcements at the girder's very end.
• Using only strand-debonding or end-zone reinforcements cannot eliminate horizontal end cracking in the BS22 hollow girder. A combination of both methods is necessary to control the happening and extent of horizontal end cracks.
• Modeling the BS22 hollow girder with four debonded strands and end-zone reinforcements, a remarkable reduction in principle stresses was achieved that could literally minimize horizontal end cracking to an acceptable range.

4. References
[1] Oliva, M. G., & Pinar, O. (2011). *Finite Element Analysis of Deep Wide-flanged Pre-stressed Girders to Understand and Control End Cracking*. Wisconsin Highway Research Program.
[2] Steensels, R., Vandewalle, L., Vandoren, B., & Degée, H. (2017). A two-stage modelling approach for the analysis of the stress distribution in anchorage zones of pre-tensioned, concrete elements. *Engineering Structures*, 143, 384-397.
[3] Bruce, S. M., McCarten, P. S., Freitag, S. A., & Hasson, L. M. (2008). Deterioration of prestressed concrete bridge beams. Land Transport New Zealand.
[4] Abdelatif, A. O., Owen, J. S., & Hussein, M. F. (2015). Modelling the prestress transfer in pre-tensioned concrete elements. *Finite Elements in Analysis and Design*, 94, 47-63.
[5] Karimi, A. K., Aasim, B. A., Tomiyama, J., & Aydan, Ö. (2017). Control of horizontal cracking at the ends of pretensioned hollow type BS12 PC-girder utilizing FEA. International Journal of Technical Research and Applications 2320-8163. Volume 5, Issue 4, (July-August) 2017), PP. 63-66.
[6] Karimi, A. K., Aasim, B. A., Tomiyama, J., Suda, Y., Aydan, Ö., & Kaneda, K. (2020). Experimental and numerical studies on the control of horizontal cracking at the ends of hollow-type pretensioned girders. SN Applied Sciences, 2(10), 1-17.
[7] Hasenkamp, C. J., Badie, S. S., Tuan, C. Y., & Tadros, M. K. (2008). Sources of end zone cracking of pretensioned concrete girders.
[8] Japan Road Association (JRA). (2012). *Specification of Highway Bridges*, part 3, Concrete Bridges.
[9] Aasim, B. A., Karimi, A. K., Tomiyama, J., & Suda, Y. (2021). Horizontal end crack control and load-bearing capacity performance of hollow-type pretensioned girders through experimentally calibrated finite element models. Engineering Science and Technology, an International Journal.
[10] Tuan, C. Y., Yehia, S. A., Jongpitaksseel, N., & Tadros, M. K. (2004). End-zone reinforcement for pretensioned concrete girders. *PCI journal*, 49(3), 68.