Study of Construction-Oriented Structural Connectors for a Temporary Bridge

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Abstract –

Temporary bridges are indeed of need after a critical disaster due to the connectivity and efficient assembly. However, the conventional structural design of these temporary bridges may be limited by the construction requirements. In this study, a new type of structural connectors is developed and beneficial for more effectively assembling ability of temporary bridges. In this development, a construction-oriented design procedure is initiated from a conceptual design and verified by an in-house, small-scale model. This conceptual connector is then modified and analyzed by sophisticated software and finally fabricated for the full-scale use. This design has a bolt-free feature and allows rotational assembly workability. The structural analysis and virtual 3D simulation are conducted to numerically verify the state-of-the-practice connector. The results from the numerical simulation imply the possibility to employ the proposed connector for a temporary bridge.

Keywords –

Bolt-free connectors; Rotational assembly workability; Temporary bridges; Construction-oriented design procedure

1 Introduction

A temporary bridge is indeed of need after a critical disaster because this structure resolves the disruptive transportation of residents and associated resources. In past, the temporary bridge designed by Yeh's team [1] was built up much faster than a commonly used temporary bridge, i.e., a culvert bridge. As analyzed from the construction video in Figure 1. Construction video of a temporary bridge. and in Table 1. Analysis of the temporary bridge construction., the erection of a glass-fiber-reinforced-polymer (GFRP) girder module costed a lot of time and human resources. The construction of the temporary bridge required five workers to adjust the orientation and alignment of this bridge module for assembly and connection. In addition, the workers had to stay at the end of the incomplete bridge structure and to accomplish the assembly, raising a concern about the worker safety. The connection between each bridge module required hundreds of bolts, resulting in tremendous manpower demands. Thus, this task should be improved by a more efficient assembly approach.

Figure 1. Construction video of a temporary bridge.

Table 1. Analysis of the temporary bridge construction.

Structural component	Task	Time[min.]/ labors/difficu-lty [1-10]
Steel segment A	Assembly	15/16/3
Steel segment B	Assembly	15/16/3
Steel segment C	Assembly	15/16/3
H-tower	Assembly	20/14/3
GFRP segment 1	Assembly	20/10/4
GFRP segment 2	Assembly	20/10/4
GFRP segment 3	Assembly	20/10/4
GFRP segment 4	Assembly	20/10/4

GFRP segment 5	Assembly	20/10/4
Steel segment A	Erection	10/7/4
Steel segment B	Erection	10/7/4
Steel segment C	Erection	10/7/4
Steel bridge panel	Installation	30/6/3
H-tower	Erection	20/15/6
GFRP 1	Erection	15/16/8
GFRP 1	Steel cable fastening	15/18/4
GFRP 2	Erection	20/16/8
GFRP 2	Steel cable fastening	20/18/4
GFRP 3	Erection	25/16/8
GFRP 3	Steel cable fastening	20/18/4
GFRP 4	Erection	30/16/8
GFRP 4	Steel cable fastening	20/18/4
GFRP 5	Erection	30/16/10
GFRP bridge panel	Installation	120/6/3

To achieve effective construction, some structural connectors featuring quick assembly and reduced manpower demands were developed. In 1994, the ATLSS system was developed to automate the beam-to-column assembly [2]. This system consisted of a quick-assembly connector and a cable-driven Stewart platform equipped on a crane. Due to expensively required equipment, the ATLSS system needed to be improved with respect to economic feasibility for the construction industry nowadays [3]. In contrast, ConXtech was a technique that provided structural connectors for quick assembly with specific constraints [4]. The ConXtech protected workers from potential risks because the working time on the assembly of structural components (e.g., workers staying at a high position) was reduced. Similarly, Kim *et al.* developed an automated beam-to-column assembly method by integrating special connectors, guiding ropes, and two developed guiding machines [5]. In addition, Liang *et al.* developed a self-rotating hook block that allowed assembling a steel beam to a steel column based on Quicon [6] connection design [7]. All these developments are directed to expedite assembly process without inducing risky manpower in construction.

In this research, the objective is to develop and design a new construction-oriented structural connector for a temporary bridge. In this development, a construction-oriented design procedure is initiated from a conceptual design and verified by an in-house, small-scale model. This conceptual connector is then modified and analyzed by sophisticated software and finally fabricated for the full-scale use. This design has a bolt-free feature and allows rotational assembly workability. The structural analysis and virtual 3D simulation are conducted to numerically verify the state-of-the-practice connector.

2 Construction-oriented structural connector design

A construction-oriented design workflow for the structural connector is proposed in this section. The workflow was iteratively improving the connector design based on a design concept described in the section as well. The section also elaborates the geometry formation.

2.1 Design workflow

Five steps were identified in the workflow in Figure 2. The design workflow for a structural connector. Step 1 is to target a structural component to redesign. The temporary bridge was constructed by connecting bridge segments. We planned to redesign the original connectors between bridge segments for quick bridge assembly. In the Step 2, by taking advantage of existing machineries we proposed possible construction methods. In the research, we aimed to use a mobile crane to assemble a temporary bridge. The following is Step 3 creating an original connector design based on the selected construction method. Finally Step 4 iteratively refines the design by the results of 3D simulation, 3D printed prototype, and finite element analysis.

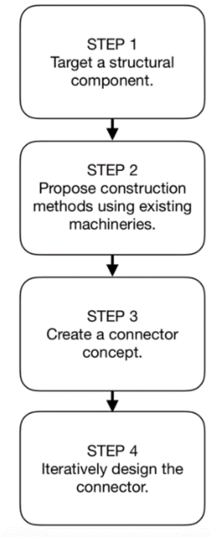

Figure 2. The design workflow for a structural connector.

2.2 Conceptual connectors and requirements

The initial connection concept was formed by a connecting mechanism and an erection method (see Figure 3. The initial connection concept). The connecting mechanism was a gravity-triggered assembly with a designed connector. When the attached connector is adjusted to the designed position a structural component applies the self-weight to finish the connection. Afterwards, the bridge segment would be temporarily fixed for workers finalizing the rest connections. The erection method was that a mobile crane lifts one end of the structural component, transports the component to where the attached connector was being placed at the designed position, and finally the crane releases the load to trigger the assembly of two structural components. Moreover, the structural behavior of the structural connector was also considered in the connection concept. The connection design must resist two axial forces, a torsional force, and a shear force. Additionally, the designed connector was attached onto the top of the connecting face of the bridge segment, and a pin-hole connection was at the bottom of the connecting face. Therefore, the designed connector and the pin-hole connection can resist negative moments and positive moments respectively.

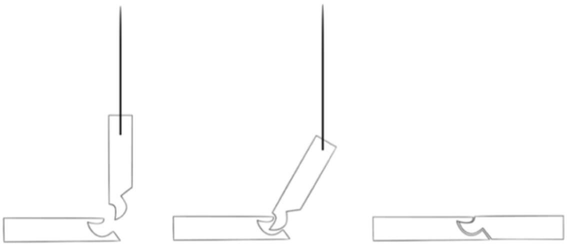

Figure 3. The initial connection concept.

2.3 Connector geometry

The workability, the strength, and the manufacturability are three major factors influencing each generation of the connector design. Because there is no definite approach to consider all major factors in a design iteration, we refined the connector design by means of divide-and-conquer approach in each design iteration. For example, although the initial connection concept met the requirements of the workability and the strength, the connection remained a challenge of producing the female connector. Therefore, for this challenge, we only focused on the production of the connector, not on the workability and the strength. We reformed the connector geometry, and the connector became the assembly of producible pieces as Figure *4*. The reformed connector. Testing the workability of connector design can be easily executed by virtual 3D simulation with physics engine and 3D printing technology. In a macro perspective, the virtual 3D simulation can simulate the assembly of the bridge segment with the designed connector. The virtual simulation helps the designer obtain the big picture of the connector application in temporary bridge construction. In contrast, the 3D printing technology can identify the problems of production from a micro perspective. Take the study for example, the tolerance and the 3D model to produce could be adjusted by taking the 3D printed prototype as a reference. The structural behavior of the designed connector can be efficiently analyzed by Finite Element Method. The manufacturability verification of the designed connector is taking the technical constraints of manufacture into the design consideration.

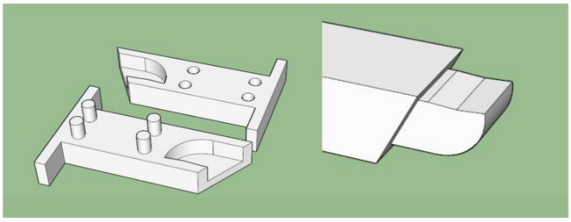

Figure 4. The reformed connector.

3 Results

This section shows the finalized connector design and two feasibility tests including a virtual assembly simulation and a structural analysis.

3.1 Finalized connector design

The final design of the connection was formed by a male connector and a female connector (see Figure 5. The finalized connector design (a) male connector, (b) female connector). Each of both was constituted of two same designed plates and an end plate. When connecting to the female connector the joint at the top of the male connector attaches onto the groove on the top of the female connector. As a result, the male connector may rotate about the joint and then complete the connection.

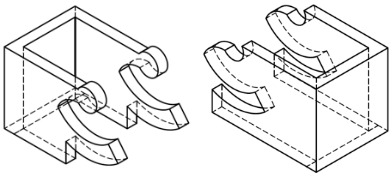

Figure 5. The finalized connector design (a) male connector, (b) female connector.

3.2 Virtual assembly simulation

We simulated the connection process in a virtual environment (see Figure 6. The virtual assembly simulation). A designed connector was attached to the bridge segment. The assembly simulation only tested the designed connection while there would be five other pin-hole connections between two bridge segments in an actual case. The simulation indicated that the alignment of the bridge segment directly influenced the operation to succeed the connection. Once the female connector and the male connector were not placed on the same plane, the connection would be stuck until the male connector was adjusted to be on the same plane of the female connector.

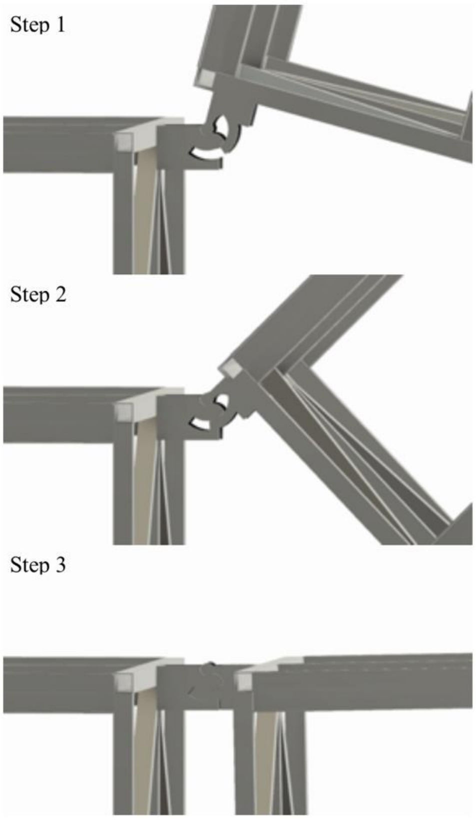

Figure 6. The virtual assembly simulation.

3.3 Results of structural analysis

We conducted four structural analyses using finite element method. Each analysis applied the designed load of the connection between bridge segments and defined the end plate of the female connector as a fixed end. The results showed the Von Mises stress.

(1) The compression test result in Figure 7. The compression test result represented that the weakest occurred at the upper part of the connection.

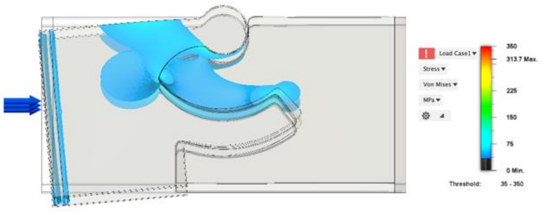

Figure 7. The compression test result.

(2) The tension test result in Figure 8. The tension test result showed that the weakest area occurred around the turning point of two discontinuous curves.

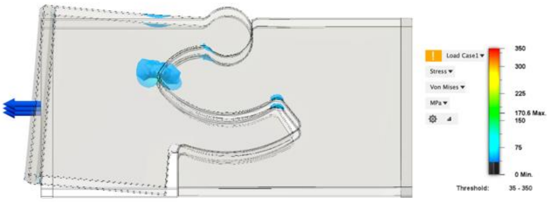

Figure 8. The tension test result.

(3) The torsion test result in Figure 9. The torsion test result showed perfect resistant to the designed torsion.

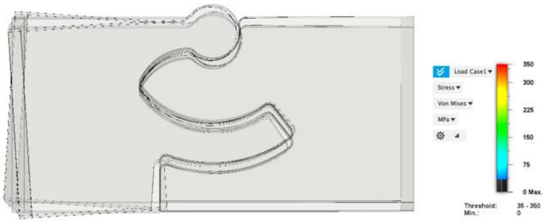

Figure 9. The torsion test result.

(4) The shear test result in Figure 10. The shear test result represented that the joint was weakest part when applying the designed load on the top surface of the male connector.

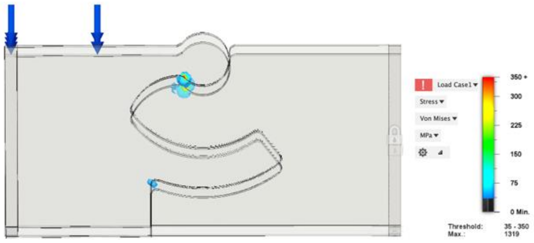

Figure 10. The shear test result.

4 Conclusion

This study proposed and designed a new type of structural connectors featuring bolt-free and rotational-assembly connection. This connector was derived from a conceptual design in the viewpoint of construction convenience and fabricated through a 3D printer. The workability of this connector was numerically and experimentally verified using a 3D manipulation platform and a small-scale model, respectively. Before turning this connector for the real-world use, the productivity and mechanics were also discussed and analyzed. Therefore, this new type of structural connectors was ready for a temporary bridge and will be experimentally evaluated in the future study.

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