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Improvement of shear capacity for precast segmental box girder dry joints by steel fiber and glass fiber

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Abstract. The use of precast segmental box girders in the bridge construction projects yields many benefits: economy, high quality, rapid construction, and minimal disruption to site. Previously, precast segments are connected together by epoxy joints. Epoxy fills in the gaps and makes strong connection, but it takes time and effort in the construction process. Later, dry joints have been introduced in the process, and hence the construction could be done much faster. However, there exists some drawback in using the dry joints. The contact surface between segments, especially at shear keys, can hardly be made smooth and well-fitted together. Consequently, the transferred shear strength cannot be developed to its full capacity. This study is an attempt to improve the capacity of shear strength of dry joints by adding steel fiber and glass fiber into concrete mixture. Considering specimens with single shear key, experiments have been conducted for shear capacities of 5 specimen types: ordinary concrete, concrete mixed with 1% and 2% steel fiber, and concrete mixed with 1% and 2% glass fiber. Results from experiments have shown that steel fiber helps increase the shear capacity of dry joints while glass fiber somehow degenerates the shear capacity and the compressive strength of concrete.

1 Introduction

Precast segmental bridges received much attention due to the method of construction that members can be precast in a factory, then transported to the site for erection (see Figure 1). Prefabricated construction provides many advantages over cast-in-place construction: reduction of time and cost, high quality control, clean construction site, and less disturbance to vicinity. Precast concrete segments are connected together at joints. Shear key plays an important role for transferring shear force at the interface of the joining in segments. Performance of the precast concrete segmental bridges depends mainly on the performance of the joints between segments. Mechanism to resist shear force comprises the combination of the friction on plain surface and the shear capacity of the keys. Two types of joints are used in practice: wet joints and dry joints. For wet joints, precast segments are glued together by epoxy. Epoxy helps to fill the gap between the interfaces, resulting in high shear capacity but brittle failure. However, applying the epoxy to each joint takes time and efforts, and hence increasing the duration of construction. On the other hand, for dry joints, precast segments are connected to each other directly without any binder in between. Due to its simplicity in method of construction, the use of dry joints becomes more and more popular since the duration of construction can be greatly reduced. Tests for shear capacities of various types of joints had been conducted [1]. AASHTO provides formula for shear capacity of dry joints and recommends that dry joints should be used in cases of external prestressing systems in areas where freeze/thaw cycles do not occur, and where de-icer chemicals are not used [2]. Rombach and Specker also proposed the formula for the shear capacity of keyed dry joints, based on numerical study [3]. These formulas by AASHTO, and Rombach and Specker tended to underestimate the shear capacity of single-keyed dry joints, but overestimate the shear capacity of multiple-keyed dry joints [4].

Fig. 1. Precast segmental box girder.

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Shear keys are typically unreinforced, and unreinforced concrete is poor in tension. When mixing fibers such as steel or glass fibers into concrete constituent, tensile strength of concrete as well as shear capacity of monolithic beams can be enhanced [5-10]. This paper presents an attempt to improve the shear capacity of dry joints by adding steel fiber and glass fiber into concrete mixture. Specimens of single-keyed dry joints have been cast with 5 different concrete mixtures and tested for shear strength. The experimental results are then compared with the formula given by AASHTO and that proposed by Rombach and Specker.

2 Specimens

In this study, steel fiber (Figure 2) and glass fiber (Figure 3) were added into concrete mixture in order to improve the shear strength of the precast concrete dry joints. To test for the shear capacity of dry joints, here we adopted the specimen with single key. Details for the shape and dimensions of the specimen used in this study is shown in Figure 4. The thickness of specimen was chosen to be 200 mm. Specimens were divided into 5 types cast with different material mixtures as follows:

Fig. 2. Steel fiber.

Fig. 3. Glass fiber.

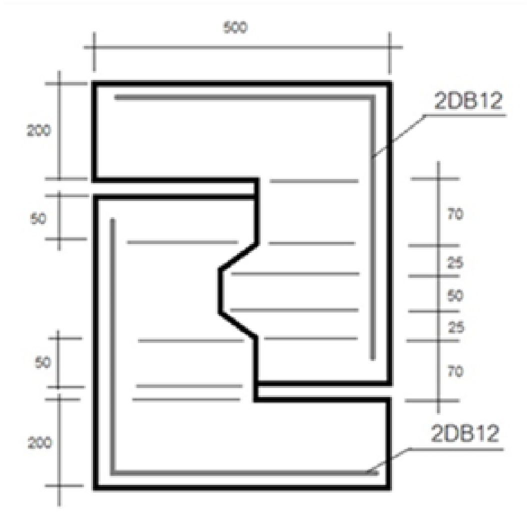

Fig. 4. Shape and dimensions of specimen, with thickness of 200 mm.

N = ordinary concrete (no fiber added)
S1, S2 = concrete mixed with 1% and 2% steel fiber
G1, G2 = concrete mixed with 1% and 2% glass fiber

Amount of the fiber added into concrete mixture is given as the percentage by weight of cement. Each type of specimen was mixed and cast for 3 samples. The female parts were cast first, and the male parts were cast on the following day by a match-cast method (see Figure 5). These specimens were cured for 28 days prior to the shear test.

Fig. 5. Match-casting of the specimens.

3 Test setup

In the test for shear capacity of the single-keyed dry joints, each pair of specimens (male and female parts) was assembled and enclosed with equipment as shown in Figure 6. Prestressing force was applied normal to the keyed joint and kept at constant stress of 1 MPa using hydraulic jack. Shear force through the keyed joint was applied by the Universal Testing Machine in the vertical direction. The applied load was measured by load cell and the relative displacement between the male and female parts was measured parallel to the applied load by LVDT (see Figure 7).

Fig. 6. Assembly of specimens and prestressing system.

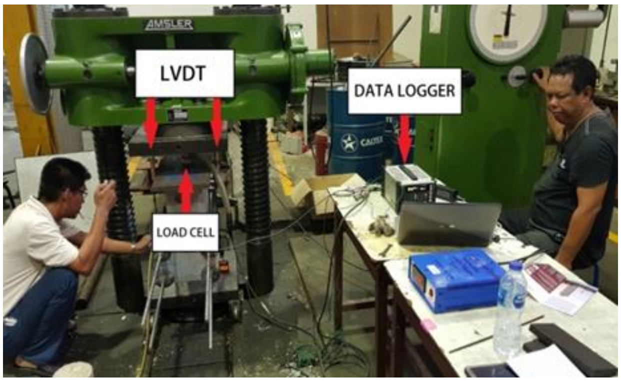

Fig. 7. Measurement for applied load and associated displacement.

4 Results and discussion

Results from the tests are plotted in Figure 8-12. Relationships between applied load (shear force) and relative displacement in the direction parallel to the applied load are shown for 5 types of specimens: ordinary concrete (no fiber added), concrete mixed with 1% and 2% steel fiber, and concrete mixed with 1% and 2% glass fiber. In these graphs, load-displacement curves show similar patterns. Load increases linearly with displacement until reaching the ultimate load, the load then drops quite immediately. This phenomenon reveals brittle failure except for concrete mixed with 2% steel fiber which load-displacement curves show some plateau after reaching the ultimate load, hence exhibiting some ductility before collapse.

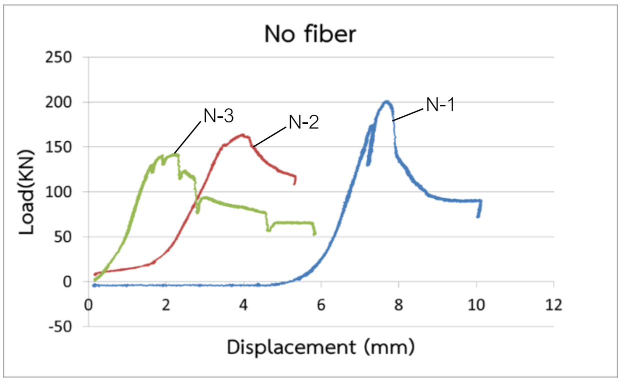

Fig. 8. Load-displacement curves for ordinary concrete (no fiber added).

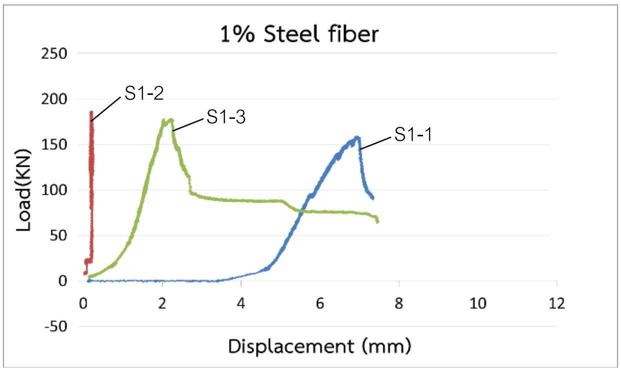

Fig. 9. Load-displacement curves for concrete mixed with 1% steel fiber.

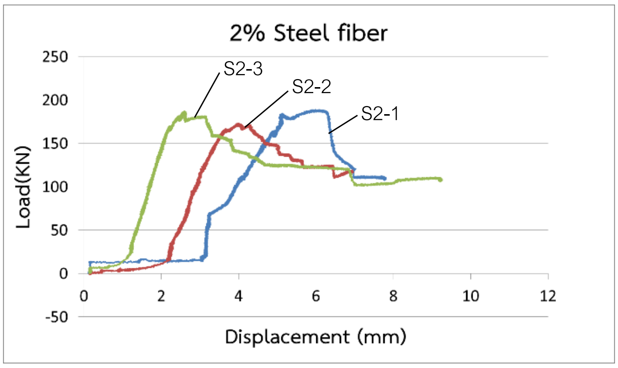

Fig. 10. Load-displacement curves for concrete mixed with 2% steel fiber.

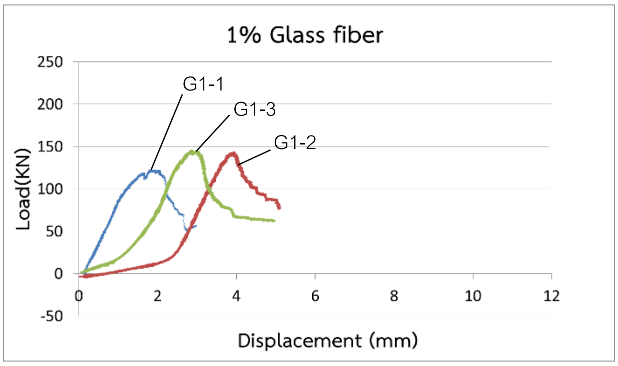

Fig. 11. Load-displacement curves for concrete mixed with 1% glass fiber.

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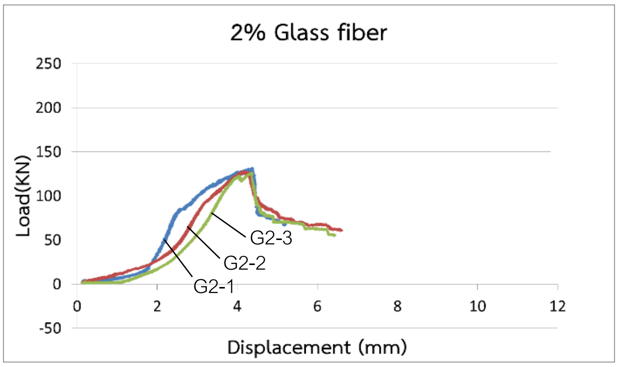

Fig. 12. Load-displacement curves for concrete mixed with 2% glass fiber.

We note here that the load-displacement curves in Figure 8-12 demonstrate some shifts or slips at initial displacement, indicating that dry joints were not fitted well together even though they were cast by a match-cast method. Also, some errors occurred on the test setup of specimen N-1 since it was the first one on trial.

The failure modes of all types of specimens were quite similar. In most of the specimens, cracks occurred along the shear plane, and collapses occurred when shear keys were sheared off throughout the shear plane, as can be seen in Figure 13-15.

The ultimate loads from shear tests along with the normalized shear strengths (shear strength divided by compressive strength) are shown in Table 1. Adding steel fiber to concrete, compressive strength does not change much, but ultimate shear force increases. Adding glass fiber to concrete, on the other hand, both compressive strength and ultimate shear force drop to certain levels. However, the normalized shear strengths (a relative parameter) of these samples give such a different manner. Mixing steel fiber 1% and 2% into concrete helps increase the normalized shear strength by 9% and 14% while mixing glass fiber 1% and 2% into concrete helps increase the normalized shear strength by 16% and 35%.

Fig. 13. Failure of ordinary concrete (no fiber added).

Fig. 14. Failure of concrete mixed with steel fiber.

Fig. 15. Failure of concrete mixed with glass fiber.

Table 1. Results from shear tests.

Specimen	Ultimate load, kN	Average ultimate load, kN	f_c', MPa	Normalized shear strength*, %
N-1	202	170	45.4	9.3
N-2	165			
N-3	142			
S1-1	159	174	43.3	10.1
S1-2	186			
S1-3	178			
S2-1	189	183	43.2	10.6
S2-2	173			
S2-3	187			
G1-1	124	138	31.9	10.8
G1-2	143			
G1-3	146			
G2-1	132	129	25.6	12.6
G2-2	128			
G2-3	127			

* Normalized shear strength is shear strength divided by f_c'.

Now, it is worth comparing the test results of dry joints, made with 5 different types of concrete mixtures, with formulas from AASHTO standard and the research by Rombach and Specker even though their limits are put only for ordinary concrete. AASHTO provided the formula for nominal shear capacity of dry joints as follows (Eq. (1) in US units, and Eq. (2) in SI units):

$$V_j = A_K\sqrt{f_c'}(12 + 0.017\sigma_n) + 0.6A_{sm}\sigma_n \quad (\lambda\beta) \tag{1}$$

$$V_j = A_K\sqrt{f_c'}(1 + 0.205\sigma_n) + 0.6A_{sm}\sigma_n \quad (\mathrm{MN}) \tag{2}$$

where

A_K is area of the base of all keys in the failure plane, in^2 or m^2.

f_c' is compressive strength of concrete, psi or MPa.

σ_n is compressive stress in concrete after allowance for all prestress losses determined at the centroid of the cross section, psi or MPa.

A_{sm} is area of contact between smooth surfaces on the failure plane, in^2 or m^2.

In their research, Rombach and Specker proposed the formula for the shear capacity of a keyed dry joint, based on the numerical models, as follows:

$$V_j = 0.14f_cA_K + 0.65\sigma_nA_{joint} \tag{3}$$

where

f_c is concrete compressive strength

A_K is area of the base of all keys in the failure plane

σ_n is average compressive stress across the joint

$A_{joint} = A_K + A_{sm}$ is area of the joint

The shear capacities from the tests of 5 different types of specimens, and the formulas provided by AASHTO, and by Rombach and Specker along with the comparison of the test results to those formulas are shown in Table 2. Actually those formulas are provided only for ordinary concrete (without any fiber). The difference of the test results to the formula by AASHTO and to the formula by Rombach and Specker are also plotted in Fig. 16. Shear capacities from tests are higher than the formula by Rombach and Specker in all specimen types. But when comparing with AASHTO, only concrete mixed with steel fiber do have higher shear capacities than AASHTO's formula. All other specimen types (ordinary concrete and concrete mixed with glass fiber) do have lower shear capacities than AASHTO's formula. Rombach and Specker's formula always gives smaller values for shear capacities, or in other word, are more conservative than AASHTO's. And AASHTO seems to overestimate shear capacities of dry joints, especially for concrete with low compressive strength. One agreement between AASHTO, and Rombach and Specker as seen in Fig. 16, shear capacity of the single-keyed dry joints increases as the amount of fiber, either steel or glass fiber, increases.

Table 2. Test results and comparison to the formulas by AASHTO, and Rombach and Specker.

Specimen type	Average ultimate load, kN	f_c', MPa	AASHTO, kN (diff.*, %)	Rombach and Specker, kN (diff.*, %)
N	170	45.4	174 (-2.5)	153 (10.9)
S1	174	43.3	171 (1.9)	147 (18.6)
S2	183	43.2	170 (7.6)	147 (24.5)
G1	138	31.9	148 (-7.0)	115 (19.7)
G2	129	25.6	134 (-3.7)	98 (31.6)

* difference of the shear capacity from test to the formula given by AASHTO or Rombach and Specker.

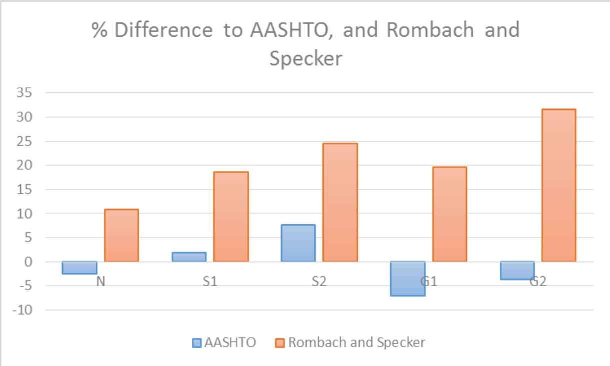

Fig. 16. Differences of the test results to the formula given by AASHTO, and to that proposed by Rombach and Specker.

5 Conclusion

This research is an attempt to improve the shear capacity of the precast segmental box girder dry joints. Considering only single-keyed dry joints, specimens are made with 5 different mixtures: ordinary concrete, concrete mixed with 1% and 2% steel fiber, and concrete mixed with 1% and 2% glass fiber. These specimens are tested for shear capacities under the confining pressure of 1 MPa. Results from test can be concluded as follows:

1. Adding steel fiber into concrete mixture results in the increase of shear capacity of the keyed dry joints, since the steel fiber help resist the tensile stress in concrete. When adding 1% and 2% of steel fiber, the normalized shear strengths of the dry joints are increased by 9% and 14%, respectively.
2. Unlike the steel fiber, adding glass fiber into concrete mixture degenerates both the compressive strength of concrete and the shear capacity of the keyed dry joints. However, when considering a relative value to the compressive strength, the normalized shear strengths are found increased by 16% and 35% for the amount of glass fiber added into concrete of 1% and 2%, respectively.
3. Failure behaviors of the single-keyed dry joints subject to shear tests are quite brittle. Except for the specimens with 2% steel fiber added, the failure behavior reveals more ductility over other types of specimens.
4. The formula for shear capacity of dry joints provided by AASHTO does not account for fiber reinforced concrete, and seems to overestimate the shear capacity of dry joints, especially for concrete with low compressive strength.
5. The formula proposed by Rombach and Specker yields smaller value for shear capacity of dry joints than AASHTO's formula, hence rather conservative. However, this formula does not account for fiber reinforced concrete, either.

Finally, results from the tests, as can be seen on the applied load-relative displacement curves, have shown that it is not easy to get a perfect fit condition for the dry joints, even with the match-cast method of only single shear key. Therefore, dry joints for precast segmental construction should be used with cautions, especially when applying this to support large loading, and more research work is needed for these dry joints, both single-keyed and multiple keyed.

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