STRUCTURAL PATTERN AND LATERAL CONSTRAINT EFFECTS ON THE TENSILE BEHAVIOR OF HEXAGONAL WIRE MESH GABION PANELS

C.W. Hsieh[1], R.S. Liu[2], I.W. Liu[3], and C.W. Chang[4]
[1] National Pingtung University of Science & Technology, Pingtung, Taiwan; Tel: +886-08-7740353; Fax: +886-08-7740477; Email: cwh@mail.npust.edu.tw
[2] National Pingtung University of Science & Technology, Pingtung, Taiwan; 886-08-7740353; Fax: +886-08-7740477; Email: M9833004@mail.npust.edu.tw
[3] National Pingtung University of Science & Technology, Pingtung, Taiwan; 886-08-7740353; Fax: +886-08-7740477; Email: iwliu@mail.npust.edu.tw
[4] National Pingtung University of Science & Technology, Pingtung, Taiwan; 886-08-7740353; Fax: +886-08-7740477; Email: M10033011@mail.npust.edu.tw

ABSTRACT

The tensile test behavior of two different structural patterns hexagonal wire mesh samples subjected to lateral unconstrained and constrained conditions were investigated. The structural patterns included three half-turn and four half-turn hexagonal wire mesh panels with and without one center cut wire in each mesh panel. The study results indicated that the ultimate tensile strength for three half-turn and four half-turn hexagonal wire mesh panels without a cut wire were similar. However, the four half-turn hexagonal wire panels showed better tensile resistance after one wire broke at the panel center. This implied that the presence of broken wires within the four half-turn hexagonal wire mesh panel showed no significant influence on the panel's tensile strength resistance. Lateral constrained wire meshes showed better tensile resistance than unconstrained samples. Due to the lateral constraint the initial slope and the first peak shown in the elongation versus tensile stress curves for the lateral constrained conditions were higher than those for the no lateral constrained condition. The presence of lateral constraint would assist in the development of a vertical or a diagonal center hole for Type A or Type B wire mesh panels with or without a center cut during the tensile tests, respectively. Generally, four half-turn hexagonal wire mesh is a better structural pattern than that the three half-turn hexagonal wire mesh in the tensile tests. A uniform lateral force distribution was observed for the four half-turn (Type B) wire mesh. A bell shaped non-uniform lateral force distribution was observed for the three half-turn (Type A) wire mesh, and the center region lateral force was higher than that for the other sides. The total lateral forces for all test constrained conditions were about the same.

Keywords: Hexagonal wire mesh, gabion, lateral constrain, river bank protection, slope stabilization, rock-fall protection.

INTRODUCTION

Steel wire gabions are widely used for river bank protection in Taiwan. However, large stones and tree trunks damage gabion wire meshes during floods and cause gabion breakage. Currently, more than 15 million square meters of wire mesh gabions have been installed for river bank protection and slope stabilization applications in Taiwan. The annual material cost for river bank protection is more than 2 trillion New Taiwan dollars. Currently the average wire mesh gabion life-time period for these applications is about seven years. If a better wire mesh construction pattern can be used in practice the replacement cost for river bank wire gabion protection would be reduced and the safety of hydraulic structures increased. The objective of this study is to investigate the tensile strength behavior of two different hexagonal wire mesh weaving patterns subjected to lateral unconstrained and constrained test conditions to provide technical information for engineers for future design and applications.

RELATED LITERATURES

In old times tree branches, rattan and bamboo were used to construct gabion nets. Gabions were filled with pebbles, boulders, or rock pieces for river bank protection or retaining structures. Due to the improvement in materials galvanized steel wire is the most common material used to build current gabion structures. The Chinese version of "Traditional Construction Technique – Introduction and Explanation of Gabions" was published by the

Public Construction Commission (PCC) (2009). Taiwan received permission from the Japanese Gabion Association to translate the design guide into Chinese. The development background, design procedure, construction details, maintenance, case studies and cost and estimation for gabions are discussed in this guide. Muhunthan et al. (2005) prepared a research report, Analysis and Design of Wire Mesh/Cable Net Slope Protection, for the FHWA, USA. The field performance, test data and design guidelines are all covered in this report. Agostini et al. (1988) presented a technical report, hexagonal wire mesh for rock-fall and slope stabilization, to discuss the engineering and technical details of hexagonal wire mesh for engineering applications. Bergado and Teerawattanasuk (2001) developed several analytical models for predicting the pullout capacity and interaction between hexagonal wire mesh and silty sand backfill. Sasiharan et al. (2006) conducted a numerical analysis to study the performance of wire mesh and cable net rock fall protection systems. Bertrand et al. (2008) used the discrete element method to model double-twisted hexagonal mesh systems. The engineering behavior of hexagonal mesh systems was studied using laboratory testing and numerical analysis. Lin et al. (2009) performed a laboratory study to evaluate the pull out behavior of two types of hexagonal wire meshes and two kinds of rigid geogrids. Lateral constrain condition and structural pattern influence on the tensile behavior of hexagonal wire meshes was investigated

TEST MATERIALS AND PROGRAM

Hexagonal steel wire mesh is commonly used to construct steel wire gabions for river bank protection and slope stability applications. Because machine-made hexagonal wire mesh panels are usually woven from more than 30 strings of steel wires, a panel would typically consist of one or two wire connections within each mesh panel. These connections are generally the wire mesh panel weak points during service life or test procedures. A large testing machine with grips is required to conduct full scale engineering tests. Therefore, it was found easier and better to construct model hexagonal wire mesh for this preliminary test program. Three half-turn (Type A) and four half-turn (Type B) hexagonal double twisted wire mesh panels were constructed and tested to evaluate the difference in engineering behavior using tensile tests. The mesh was woven using a nominal diameter of 1.18 mm galvanized steel wire. The tensile strength of the steel wire is 510 N/mm2. Forty-three (43) mm by 50 mm mesh opening was used to construct a near perfect hexagonal pattern wire mesh. The test model hexagonal wire mesh opening is about one third in size in compared with typical full size wire meshes with 120mm by 150mm openings. ASTM A975 and A370 test methods were used in these tests. Wire mesh panel tensile tests with and without a center cut wire were conducted. The wire mesh tensile behaviors for unconstrained and constrained lateral conditions were also evaluated. The difference in weaving pattern between three half-turn (Type A) and four half-turn (Type B) double twisted hexagonal wire meshes is demonstrated in Figs 1 and 2, indicated as Type A and Type B wire mesh. As shown in the Figs top-down and diagonal weaving patterns were observed for three half-turn and four half-turn wire meshes, respectively. Different engineering behavior can be expected due to the difference in weaving structure of these two types of meshes. In addition, the lateral constrained and unconstrained condition effect was also evaluated. The tensile test sample setup for unstrained and constrained conditions is shown in Figs 3 and 4, respectively. The tensile test panel dimension was 563mm by 300mm. As shown in the Figs 4 and 3 load cells were mounted on the test frame to measure the lateral forces during the tensile tests.

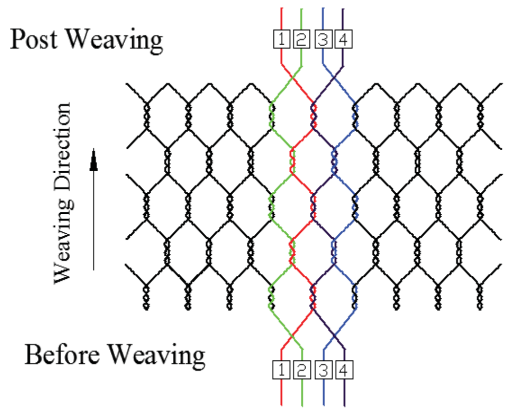


Fig. 1 Schematic view of wire weaving pattern for Type A mesh.

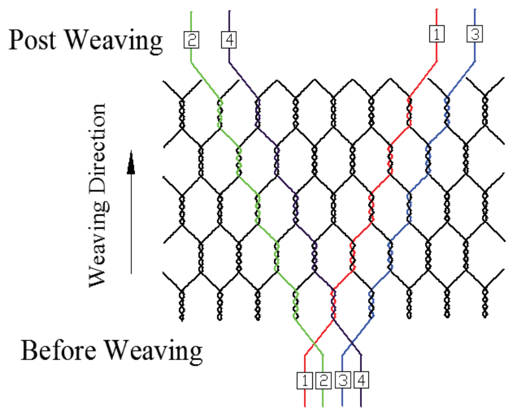


Fig. 2 Schematic view of wire weaving pattern for Type B mesh.

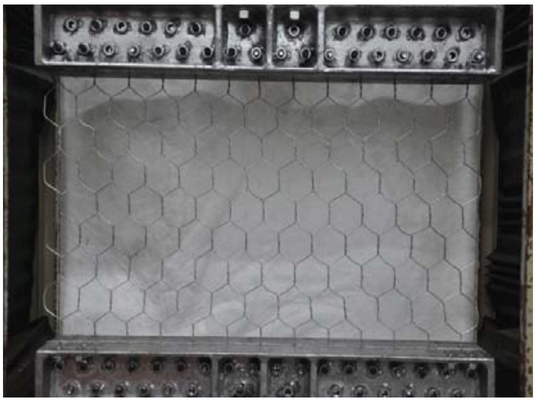
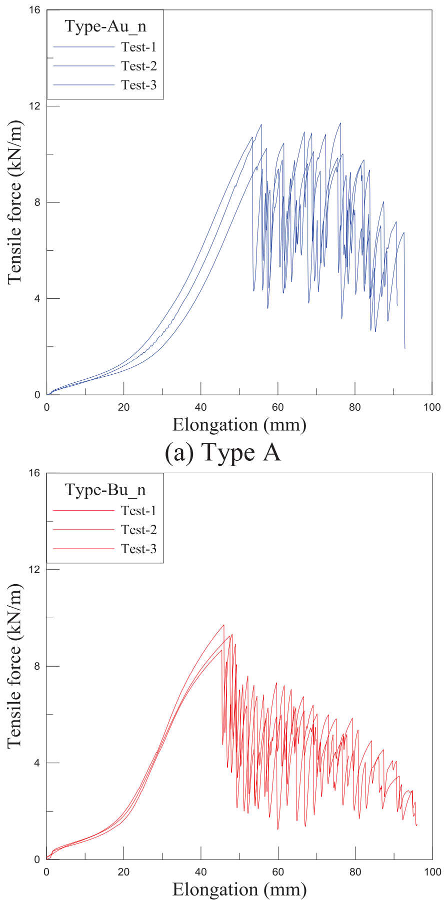


Fig. 3 Schematic view of the setup for no lateral constrained tensile test.

Fig. 4 Schematic view of the setup for lateral constrained tensile test.

RESULTS AND DISCUSSIONS

A series of wide width tensile tests were conducted according to the ASTM D975 test method. Tensile tests for Type A and Type B double twisted hexagonal wire mesh panels subjected to lateral constrained and unconstrained conditions were conducted. Tensile tests for test panels with and without one cut center wire were also conducted to evaluate the wire mesh behavior due to the mesh wire breakage effect. A minimum of three repeated tests were conducted for each test condition to prove the repeatability of the engineering behavior. Very good tensile test repeatability was found for Type A and Type B double twisted hexagonal wire mesh panels without lateral constraint condition, as shown in Fig 5. The representative test results are discussed. The tensile test results and discussions for Type A and Type B hexagonal wire mesh panels subjected to no constrained and constrained conditions are discussed as follows. Table 1 summarizes the test material types and test conditions. The test conditions are represented using two letters; the first letter indicates the test material and the second letter shows the cut wire condition. As shown in the table the connecting lines indicate the comparison between the test conditions. The tensile test comparison results subjected to different lateral constraint conditions will be discussed thereafter.



(a) Type A

(b) Type B

Fig. 5 Three repeated tensile test results for Type A and B mesh panels without lateral constraint and no cut center wire.

Table 1 Summary of the test conditions and comparison cases.

Condition	Type-A		Type-B	
	Au	Ac	Bu	Bc
No lateral constraint	●	——	●	
		●	——	●
	● —— ●		● —— ●	
Lateral constraint	●	——	●	
		●	——	●
	● —— ●		● —— ●	

No Lateral Constrained Tensile Tests

The no lateral constrained tensile test is commonly used in material testing. A wide width sample is usually used to reduce the necking behavior during the test. According to general testing practice near two (in width) to one (in length) ratio wire mesh panels were used in these tests. The test panel dimensions were 563mm by 300mm in this study. The tensile test results for the no lateral constraint condition for Type A and Type B wire meshes without and with a center cut wire are discussed as follows.

Tensile tests without a center cut wire

The typical tensile test results for three half-turn (Type A) and four half-turn (Type B) hexagonal wire mesh panels are shown in Fig 6. As shown in Fig 6 the initial tensile stress versus elongation curves for both types of wire mesh are quite similar to each other. The tensile stress versus elongation curves can be divided into four stages. According to observation the elongations were contributed from the straight and twisted wire sections of the hexagonal wire mesh for stage-1 and stage-3. The elongation for stage-2 was a transition between stage-1 and stage-3. The first and maximum peak tensile stress occurred at elongation around 50 to 60 mm for both wire types. After the tensile stress reached a peak, a drop in tensile stress associated with mesh elongation and steel wire de-twisting occurred near the broken wire. In general, one peak stress is associated with breaking one steel wire. The elongation after the first peak was considered as the test stage-4. The peak tensile stress for Type A wire mesh was slightly higher than that for Type B wire mesh. However, several similar consecutive peak tensile stresses were observed after the first and highest peak tensile stress occurred as the elongation continued. A larger amount of elongation between each consecutive broken wire was also observed for the Type A wire mesh due to wire de-twisting around the broken wires. This implied that Type A wire mesh elongated more and quicker than Type B wire mesh. The consecutive peak tensile stresses for the Type B wire mesh panel decreased as the elongation increased. However, the elongation between each consecutive break was significantly less than that for Type A wire mesh. This implied that Type B wire mesh deformed less when subjected to tensile loads.

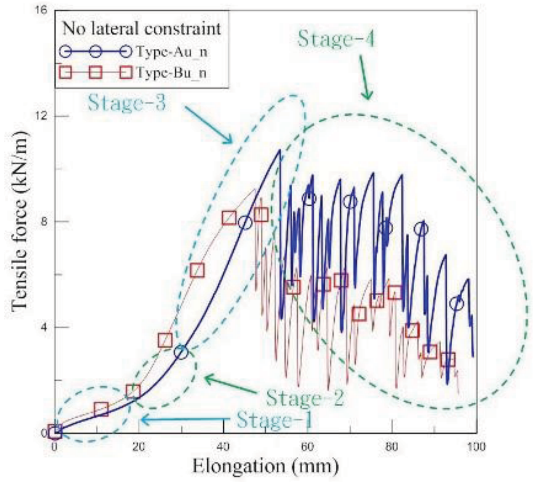


Fig. 6 Typical tensile test results of Type A and B mesh panels without lateral constraint and without one center cut.

Tensile test of panel with a center cut

In many cases steel wires in a panel would be broken by stones or other objects during panel service life. Therefore, it is necessary to study the engineering behavior of steel wire mesh with some steel wires broken. A series of tensile tests for Type A and Type B hexagonal wire mesh panels with one cut center wire was performed. The typical tensile stress versus elongation curves for wire meshes without lateral constraint and with a cut center wire are shown in Fig 7. As shown in the Fig the maximum tensile stresses for both wire mesh types were about 9 kN/m and quite similar to each other. However, the elongation at maximum tensile stress for Type A wire mesh was much greater than that for Type B wire mesh. Typical failure modes for the Type A and Type B wire mesh panel tensile tests with one cut center wire are shown in Figs 8 and 9. As shown in Figs 8 and 9 steel wire de-twisting occurred around the cut wire, inducing the mesh panel to divide into two parts at the center. The steel wire de-twisting around the cut wire in the tensile test for Type B wire mesh was relatively less significant. Several broken wires occurred around the cut wire as shown in Fig 9.

Comparing the typical tensile force versus elongation curve for Type A wire mesh with and without one cut center wire, a significant difference in wire mesh elongation occurred between the two test conditions as shown in Fig 10. Greater elongation, wire de-twisting around the cut wire and a large hole formed at the panel center are clearly shown in Fig 8 for Type Ac_n (cut wire) case. In contrast, less elongation and several broken wires were observed near the grips for Type Au_n shown in Fig 11.

Comparison of typical tensile test curves for Type B wire mesh with and without one cut center wire was quite similar to each other, as shown in Fig 12. The major difference is the first elongation at break. The first elongation at break for the cut center wire case (Type Bc) was about 10mm less than that for the Type Bu case. This implied that the presence of one cut center wire in the Type B mesh panel showed no significant effect on the tensile behavior. However, the Type A mesh panel showed a larger elongation and less tensile resistance with a cut center wire (Type Ac_n) compared with the other three cases (Type Au_n, Type Bu_n and Type Bc_n) for no lateral constraint condition. Tensile failure mode of Type B mesh without lateral constraint (Type Bu_n) is shown in Fig 13.

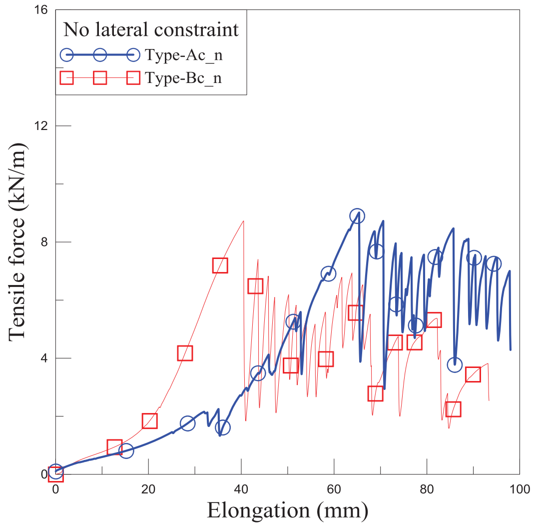


Fig. 7 Typical tensile test results for Type A and B mesh panels with one center cut wire (no lateral constrain).

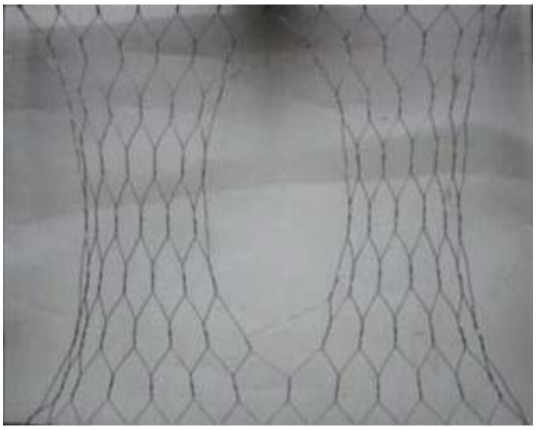


Fig. 8 Tensile failure mode of Type A mesh panel with one center cut wire (Type Ac_n).

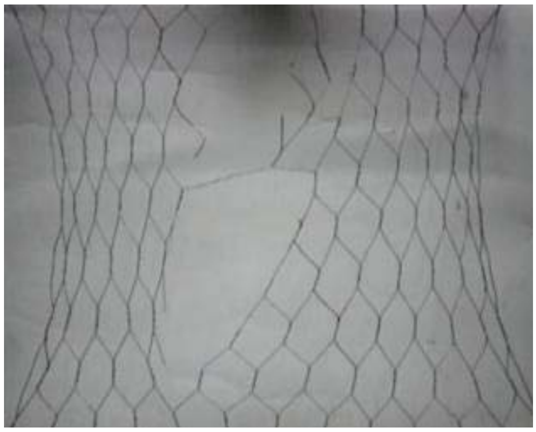


Fig. 9 Tensile failure mode of Type B mesh with one center cut wire (Type Bc_n).

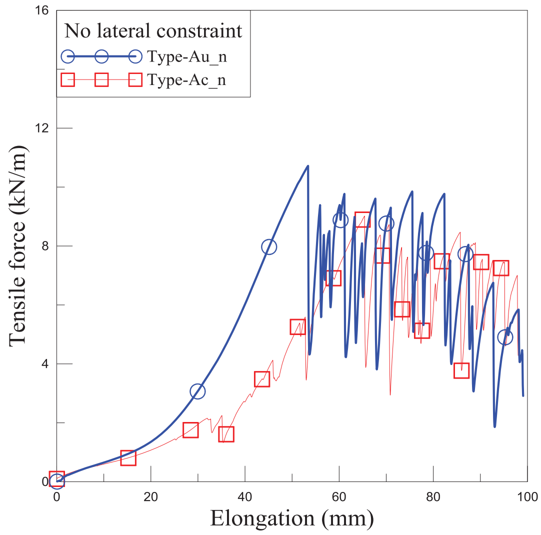


Fig. 10 Typical tensile test results for Type A mesh panels with and without one cut wire (No-constrained condition).

Fig. 11 Tensile failure mode of Type A mesh panel without lateral constraint (Type Au_n).

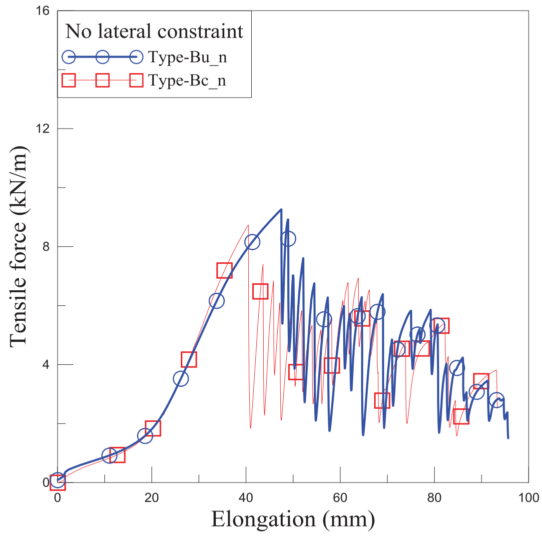


Fig. 12 Typical tensile test results for Type B mesh panels with and without one cut wire (No-constrained condition).

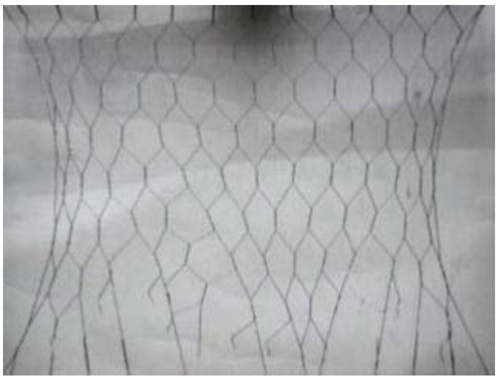


Fig. 13 Tensile failure mode of Type B mesh without lateral constraint (Type Bu_n).

Lateral Constrained Tensile Tests

In most practical steel wire mesh applications the wire meshes are subjected to tensile forces in conjunction with lateral constraint deformation. Therefore, it is more realistic to apply lateral constraint conditions to the mesh panel during the tensile test. A lateral constraint mechanism was used in the FHWA wire mesh tensile test study in "Analysis and Design Wire Mesh/Cable Net Slope Protection" (Muhunthan et al., 2005). Therefore, lateral constraint tensile tests were also investigated in this study. The Type A and Type B hexagonal wire mesh tensile tests subjected to lateral constraint with and without a cut center wire are discussed as follows.

Constrain without a center cut

The typical tensile force versus elongation curves for Type A and Type B wire meshes subjected to lateral constraint conditions are shown in Fig 14. Due to the lateral constraint the slope of elongation versus tensile force curves for both type meshes are quite similar to each other. The initial slope is also much higher than that for the no lateral constraint condition. The maximum tensile stress and associated elongation for type A wire mesh was about 2 kN/m higher than that for Type B wire mesh. The elongation between each consecutive broken wire was only about 1 to 2 mm for Type B wire mesh. In contrast the elongation between each broken wire for Type A wire mesh ranged from 2 to 8 mm. As shown in Figs 15 (a) and (b) the failure modes for Type A and Type B wire mesh panels were completely different. A large center vertical hole with only 3 to 4 broken wires with de-twisted wires around the broken wires were observed for the Type A wire mesh. Several broken wires near the grips and an associated diagonal hole were observed for the type B wire mesh. The difference in tensile test behavior is related to the structural pattern.

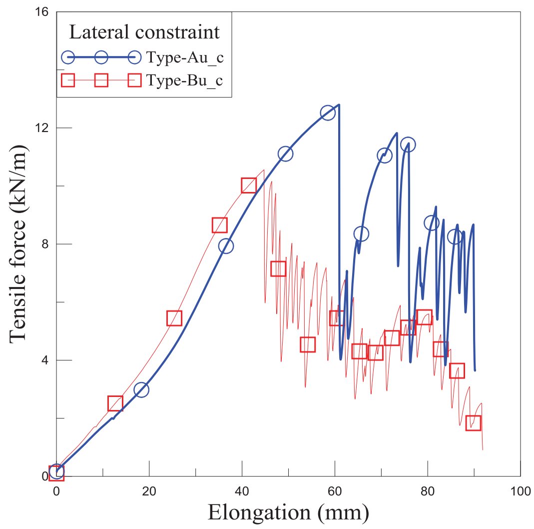
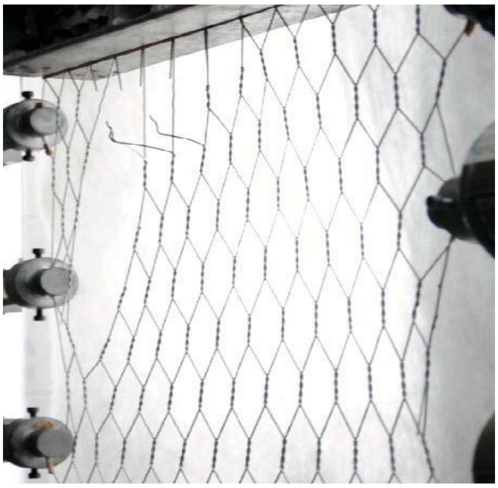


Fig. 14 Typical tensile test results for Type A and B mesh panels with lateral constraint and without one center cut wire.

(a) Type Au_c



(b) Type Bu_c

Fig. 15 Typical tensile failure modes of Type A and B mesh panels with lateral constraint and without one center cut wire.

Constrain with a center cut

The typical tensile stress versus elongation curves for Type A and Type B wire meshes subjected to lateral constraint with a cut center wire are shown in Fig 16. As shown in the Fig the maximum tensile stresses for both wire mesh types were about 10 kN/m and quite similar to each other. However, the elongation at maximum tensile stress for Type A wire mesh was much greater than that for Type B wire mesh. As shown in the failure mode picture for the Type A wire mesh (Fig 17(a)), de-twisted wires were present around the cut wire which induced the mesh panel to divide into two parts at the center. In addition, the elongation between each consecutive broken wire was about 6 to 8 mm. In contrast several broken wires near the cut wire and a diagonal hole are shown in Fig 17(b) for Type B wire mesh. The elongation between each consecutive broken wire was only 1 to 3 mm. The difference in tensile test behavior due to the structural pattern effect is also clear.

Comparing the typical tensile stress versus elongation curve for Type A wire mesh subjected to lateral constraint with and without one cut center wire is shown in Fig 18. Due to the difference in structural pattern the initial slope of elongation versus tensile stress curves and the peak tensile stress of these two types of wire meshes were quite different from each other. However, the failure modes shown in Figs 15(a) and 17(a) were similar for both wire meshes.

Typical tensile test curve comparison for Type B wire mesh subjected to lateral constraint with and without one cut center wire was quite similar, as shown in Fig 19. The difference in failure mode is the location of the holes. A diagonal hole would occur near the cut wire for the Type Bc case, shown in Fig 17(b). However, a diagonal hole would be randomly observed near the weakest wire location on the test panel for the Type Bu condition, shown in Fig 15(b). This also implied that the presence of one center cut wire in the Type B mesh panel showed no significant effect on the tensile behavior.

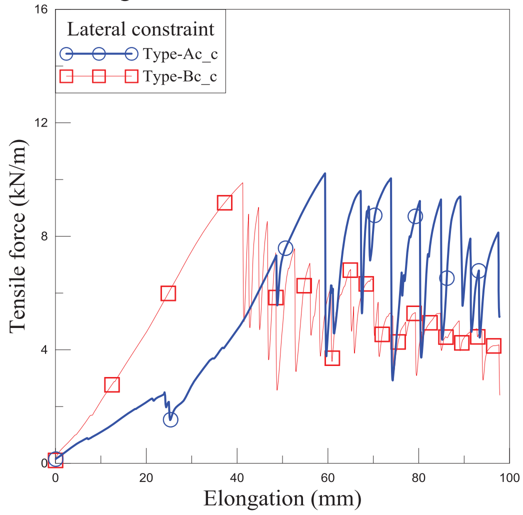
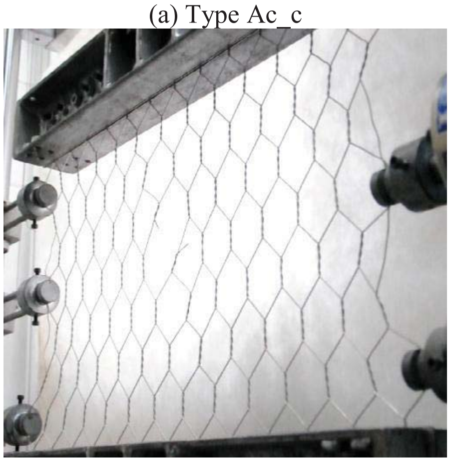


Fig. 16 Typical tensile test results of Type A and B mesh panels subjected to lateral constraint with one center cut.

(a) Type Ac_c



(b) Type Bc_c

Fig. 17 Typical tensile failure modes of Type A and B mesh panels subjected to lateral constraint with one center cut.

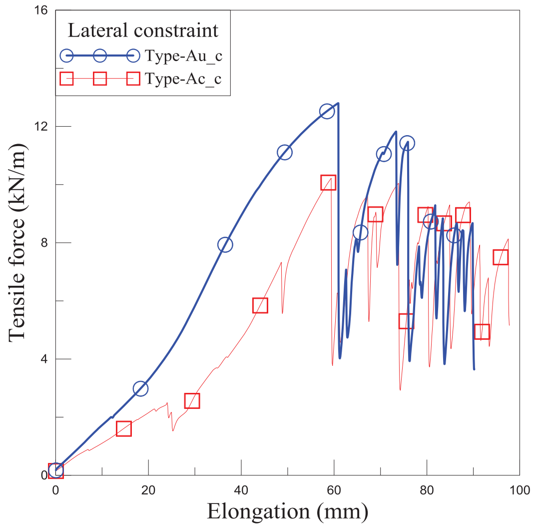


Fig. 18 Typical tensile test results for Type A mesh panels subjected to lateral constraint with and without one cut wire.

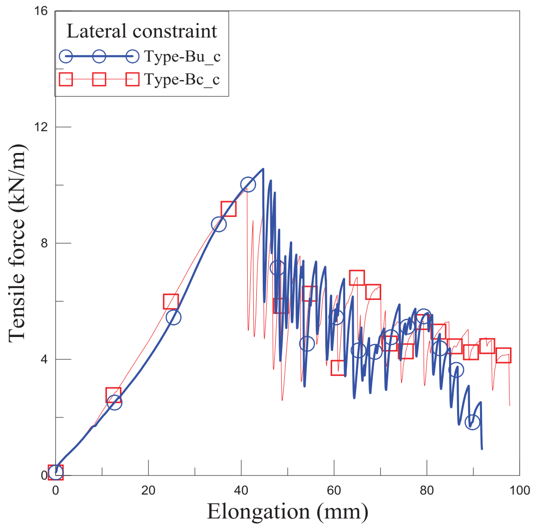


Fig 19 Typical tensile test results for Type B mesh panels subjected to lateral constraint with and without one cut wire.

Lateral Constrain Effects on Tensile Test Behavior

The tensile test is a widely used test to evaluate the general behavior of a material. Generally, wide width tensile tests with no lateral constraint are commonly used. A two to one ratio in size sample is normally used to eliminate the necking phenomenon. Tensile test results for difference types wire meshes and test conditions with and without lateral constraint will be discussed in this section to provide general information for lateral constraint effects on the tensile behavior of hexagonal wire meshes. Tensile tests for two types of hexagonal wire meshes with and without a center cut wire subjected to constrained and un-constrained conditions will be discussed as follows.

Without a center cut wire

The typical tensile test results for Type A hexagonal wire meshes with and without lateral constraint are shown in Fig 20. Due to the lateral constraint the initial slope and the first peak shown in the elongation versus tensile stress curve for the lateral constrained condition is higher than that for the no lateral constrained condition. The failure modes shown in Figs 11 and 15(a) are completely different from each other. A center wire broke first and a center vertical hole developed as the tensile force increased for the lateral constrained condition. As shown on the elongation versus tensile stress curve, around 5 mm to 10 mm elongation between consecutive broken wires (peaks) implied wire de-twisting near the broken wires had occurred, as shown in Fig 15(a). However, consecutive broken wires were observed for the no lateral constrained condition, as shown in Fig 11.

The typical tensile test results for Type B hexagonal wire meshes with and without lateral constraint are shown in Fig 21. Similarly, the initial slope and the first peak stress of elongation versus tensile stress curve for the lateral constrained condition was higher than that for the no lateral constrained condition due to the lateral constraint. After the peak the consecutive broken wires breakage failure mode with relatively short (1 mm to 4 mm) elongations was observed in both cases. However, a diagonal hole associated with some broken wires developed as the tensile force increased for the lateral constrained condition, as shown in Fig 15 (b).

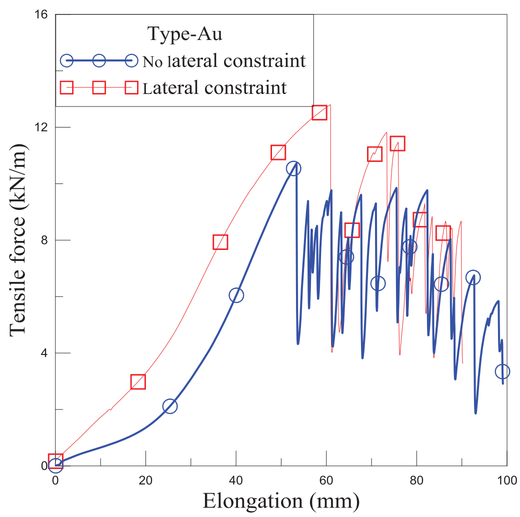


Fig. 20 Typical tensile test results for Type A wire mesh subjected to lateral constraint and un-constrained conditions.

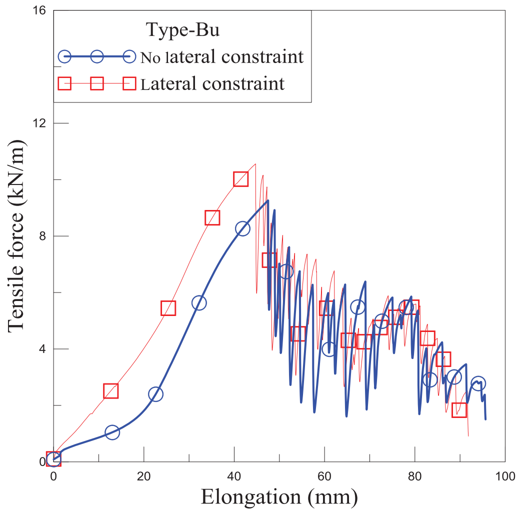


Fig. 21 Typical tensile test results for Type B wire mesh subjected to lateral constraint and un-constrained conditions.

With a center cut wire

Due to the top to down weaving pattern for Type A hexagonal wire mesh relatively flat initial elongation versus tensile stress curves were observed for both the constrained and un-constrained conditions, as shown in Fig 22. After the peak similar failure modes and elongation versus tensile stress curves were observed for both cases, as shown in Figs 8, 17(a), and 22. However, the first peak elongation for the constrained condition was slightly higher than that for the unconstrained condition.

As expected, a relatively higher initial slope and peak tensile stress were observed for the Type B wire mesh subjected to the lateral constrained condition, as shown in Fig 23. Development of a diagonal center hole near the center cut wire was clearer for the lateral constrained condition (Fig 17(b) than the un-constrained condition (Fig 9). The presence of lateral constraint showed some influence on the center hole development for the tested wire mesh panels.

Distribution of lateral tensile forces

Three load cells were mounted vertically on the lateral constraint tensile test frame to measure the lateral forces during the tests. The lateral tensile forces distribution for the two types of wire meshes with and without a center cut wire are shown in Fig 24. Due to the top down weaving pattern the necking phenomenon was relatively more significant for Type A. Therefore, higher lateral tensile forces were measured at the center load cell for the Type Au and Type Ac cases. The center lateral force for Type Ac was relatively less than that for Type Au due to the presence of a cut wire. The lateral forces distribution was relatively uniform for both Type Bu and Type Bc cases. This is related to the diagonal weaving pattern for Type B wire mesh. The summation of three lateral forces for all cases was about the same. The total lateral force was about 1.3 kN for all tested constraint conditions.

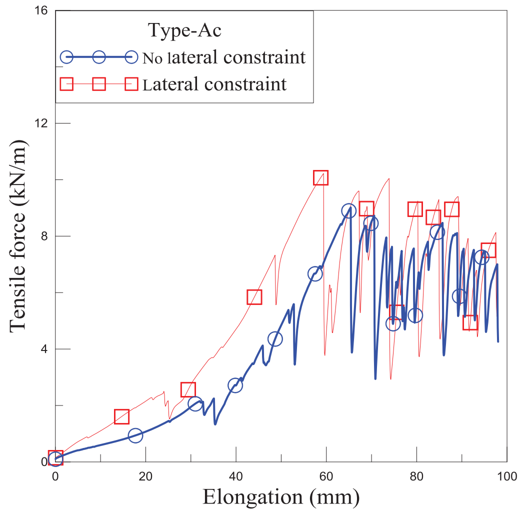


Fig. 22 Typical tensile test results for Type A wire mesh subjected to lateral constrained and un-constrained conditions with a center cut wire.

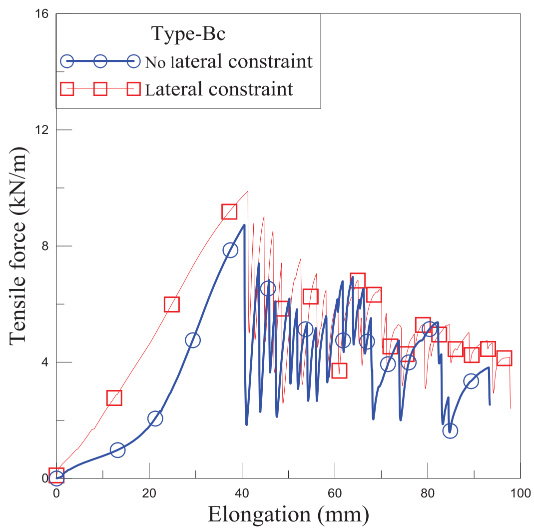


Fig. 23 Typical tensile test results for Type B wire mesh subjected to lateral constrained and un-constrained conditions with a center cut wire.

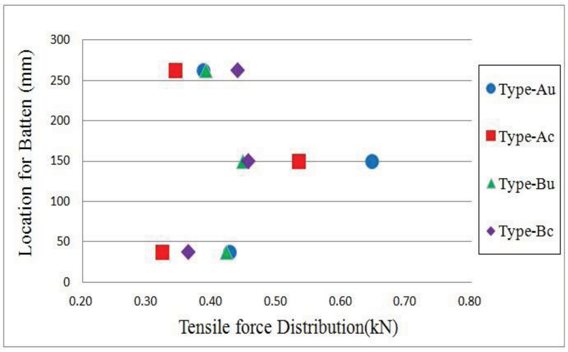


Fig. 24 The distribution of lateral tensile forces for the two types of wire meshes with and without a center cut wire.

CONCLUSIONS

The average replacement time for wire mesh gabions used for river bank protection and stabilization applications is about seven years in Taiwan. The annual material cost for this is more than 2 trillion New Taiwan dollars. This study investigated the tensile strength behavior of three half-turn (Type A) and four half turn (Type B) hexagonal wire meshes using a series of tensile tests. The lateral constraint condition and with and without one center cut wire in the test panels were also investigated. The results from this study provide technical information for engineers to reduce the replacement costs for wire gabions, improve the design and increase the safety of hydraulic structures.

Top-down and diagonal weaving patterns were observed for three half-turn (Type A) and four half-turn (Type B) wire meshes, respectively. The weaving pattern has a significant influence on the tensile strength behavior of hexagonal wire mesh. The ultimate tensile strength for three half-turn or four half-turn hexagonal wire mesh panels without cut wires were similar. However, the four half-turn hexagonal wire panels showed better tensile strength after one wire was cut at the panel center. This implied that the presence of broken wires within the four half-turn hexagonal wire mesh would show no significant influence on the panel tensile strength. Four half-turn hexagonal wire mesh is a better weaving pattern than three half-turn hexagonal wire mesh for slope stability and river bank protection applications.

Due to the lateral constraint the initial slope and the first peak shown in the elongation versus tensile stress curves for the lateral constrained condition was higher than that for the no lateral constrained condition. The presence of lateral constraint would assist the development of a vertical or a diagonal center hole for Type A or Type B wire mesh with or without a center cut wire during the tensile tests, respectively.

Due to the differences in weaving pattern and the lateral constraint effect a uniform lateral force distribution was observed for Type B wire mesh. A bell shaped non-uniform lateral force distribution was observed for Type A wire mesh. The center region lateral force was higher than that for the other sides. The total lateral forces for all tested constrained conditions were about the same.

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