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Research on the mechanical properties of membrane connections in tensioned membrane structures

Yingying Zhang*[1,2], Qilin Zhang[2], Yang Li[3] and Lu Chen[4]

[1]*Jiangsu Key Laboratory of Environmental Impact and Structural Safety in Engineering, China University of Mining and Technology, Jiangsu Xuzhou, China*
[2]*College of Civil Engineering, Tongji University, Shanghai, China*
[3]*Shanghai Urban Construction and Communications Commission, Shanghai, China*
[4]*Shanghai Tongji Construction Quality Inspection Station, Shanghai, China*

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Abstract. As an important part, the connections generally are important for the overall behavior of the structure and the strength and serviceability of the connection should be ensured. This paper presents the mechanical properties of membrane connections in tensioned membrane structure. First, the details of common connections used in the membrane structure are introduced. Then, the common connections including membrane seam, membrane-flexible edge connection and membrane-rigid edge connection are tested and the corresponding failure mechanisms are discussed. Finally, the effects of connection parameters on the connection strength are investigated and proper connection parameters are proposed. The strength reduction factors corresponding to different connection types are proposed, which can be references for the design and analysis of membrane structures.

Keywords: membrane connection; connection strength; orthogonal test; strength reduction factor

1. Introduction

Tensioned membrane structures have been widely used in the large-span buildings, such as stadiums, gymnasiums, exhibition halls, and airport lounges. This popularity is due to their engineering benefits such as aesthetic shape, low construction cost, fast installation, structurally efficient, capability of covering large space, and natural lighting. In addition, tensioned membrane structures consume less non-renewable resources and are regarded as an environmentally friendly and sustainable construction. The nature of tensioned membrane structure is achieving the structural stiffness by virtue of special geometric shapes with initial prestress in the membranes and cables. These structures combine striking architectural forms with high levels of structural stability and durability, with expected lifespans in excess of thirty years (Foster 2004). Key to achieving these high levels of performance is accurate modeling of the form and behavior of the structure, including incorporation of the inherent uncertainties in all aspects of the design process (Gosling 2013, Bridgens 2012).

*Corresponding author, Associate Professor, E-mail: zhangyingying85@163.com

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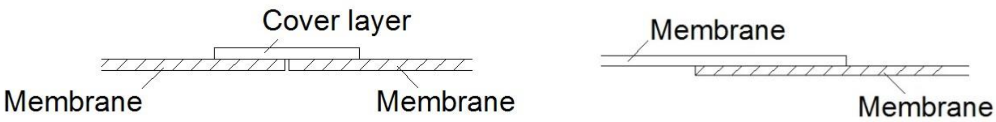


Butt seam Overlap seam

Fig. 1 Membrane seam

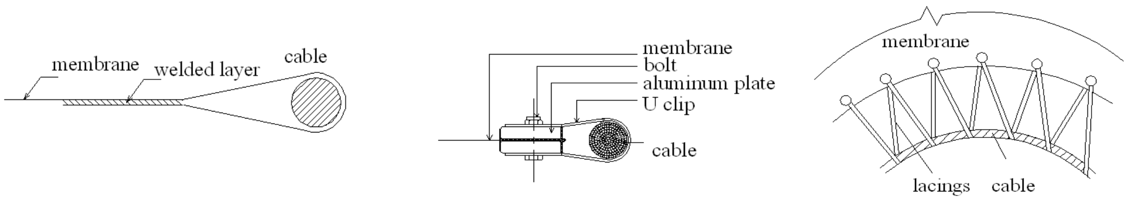
The design and analysis of fabric structures is more dependent upon computers than most of other structural systems, as they defy the linear analysis routine for concrete, steel, timber or composite structures. Developing the design of membrane structure is an optimization process in which both the overall design and the details are developed simultaneously. Detailing involves considering the connections of different parts of the structure, while remaining aware of its general evolution. The details express both its function and how the whole structure works. Unlike conventional structures, the shape of a tensile structure cannot be prescribed, but must take a 'form-found' shape determined by equilibrium and geometric constraints. Further, in tensioned membrane structures, boundary fastener is the important equipment to apply the membrane prestress. Details generally are vital to the overall stability of the structure although some may be of only minor importance. As an important part, the connections generally are important for the overall behavior of the structure and the strength and serviceability of the connection should be tested in advance as well as during the fabrication process (Foster 2004).

1.1 Connections of membrane structure

There are several types of membrane connections, membrane seams, rigid edge connection, flexible edge connection, field supports, and others.

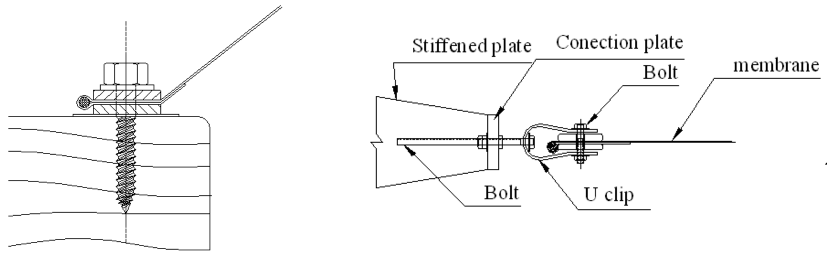
Membrane seams are the linear connection between adjoining panels of membrane. There are six types of seams including welded seams, glued seams, combination seams, stitched seams, laced seams, and clamped seams. As shown in Fig. 1, Welded seams are most commonly used because of their inherent water tightness and the controlled production processes employed. The strength of welded seam depends on the bonding of the coating to the weave and the connection width of the seam. There are different types of construction for welded seams, of which the most common is the overlap seam followed by the butt seam. Glued seam is always used in making patch repairs to PVC coated membranes, but is expensive and labor intensive. It is always used in elastomer coated materials like Hypalon or Silicone coated fabrics. For tensioned fabric structures, stitched seams are generally limited to the connection of specific parts, and can be used for high loads especially for PTFE fabric. Stitched seams are mainly used for non-coated fabrics or non-weldable fabrics. Seams which use a combination seam of both stitching and welding can provide an extra level of security in extreme environments, but they are only suitable for stitchable materials, for example, PVC coated polyester and woven PTFE cloth, but not PTFE coated glass (Foster 2004).

As shown in Fig. 1, there are several types of membrane-flexible edge connection used in actual engineering, for example, membrane pocket connection, *U* clip connection and laced connection et al. Flexible curved edges allow the prestressing of the fabric as the result of a tension force developing in the boundary element. The transmission of force between the membrane and the boundary line of support occurs by the keder bearing against the edge of the clamp plates. It



Membrane pocket connection *U* clip connection laced connection

Fig. 2 Membrane-flexible edge connection



Membrane-timber structure *U* clip connection

Fig. 3 Membrane-rigid edge connections

can transfer the force between the membrane and the cable uniformly. The membrane pocket can be made by turning the fabric's edge back on itself and this needs to be done in discrete lengths for the fabric to be able to conform to the curvature of the cable. The strength of membrane pocket depends on the welded width, which is similar to the welded seam.

As shown in Fig. 3, rigid edges are edges where the fabric is held continuously by a supporting structure having much greater lateral stiffness compared with that of the fabric, such as metal structure, concrete structure, and timber structure. However, in essence, it is the connection of membrane and metal structure. There are three principal types of connections, cable pocket, *U* clip connection and clamp plate connection, which is similar to the membrane-flexible edge connection.

1.2 Design criteria of membrane connections

The details must work in a way that is consistent with the designer's modeling of the structure, whether physical or numerical. Details must be installable as well as able to function satisfactorily throughout their lifetime. Details generally are vital to the overall stability of the structure although some may be of only minor importance. The followings should be taken into account in the design (Foster 2004).

(1) Direct load path

Tensioned membrane structures are stable due to their doubly curved forms generated by tension force equilibrium. The detail elements must be able to respect the load path geometry as external loading conditions change. The design and execution of such elements need to be precise and in accordance with the membrane geometry.

(2) Flexibility for displacements

The displacements of tensioned membrane structures produced by external loads are relatively large compared with those of more conventional building systems. This characteristic has to be considered during all stages of the design of tensioned membrane structures.

(3) Strength, stability and durability

Strength, stability and durability are basic structural requirements for all building systems. For membrane structures, well-processed details are important for ensuring good structural performance. The design must take into account the possible local stress concentration and the degradation of connection performances.

(4) Structural integrity

The connections should be precise and small, which is consistent with geometric shape, artistic appearance and architectural requirements. Designs have to be such that in the event of the failure of one or more membrane fields within a roof, the whole system does not collapse, and heavy elements such as masts are arrested by a fail-safe system. Some security elements may need to be added into the structure's system.

(5) Pretension and adjustability

The dimensions of the individual panels of cloth which are to form the membrane surface are reduced by a small percentage for compensation, such that when the whole membrane is stretched into the intended position. During the installation of the membrane, temporary equipment such as hydraulic jacks is needed to develop the intended prestress. Such jacking forces are mainly applied in the corner points of the membrane edge and at internal suspension points, or mast and anchor cable footings. Fine adjustments can then be applied where necessary by devices distributed among strategic points to provide a uniform adjustment of the membrane's tension.

Since the birth of modern tensioned membrane structures, many researchers have studied the mechanical properties of connections in the membrane structures. Chen carried out a series of experiments on the width of backup strip for PVC welded membrane and lapped width for PTFE welded membrane (Chen 2007). Skelton investigated the strength of seaming efficiency of four lightweight coated nylon fabrics and found loss of seaming efficiency was shown to be related to fabric pulled-out at the seams (Skelton 1971). H. Kim studied the stress transition mechanism of clamping part of membrane structures and the fracture characteristics of membrane material in bolting part (Kim 2005). J. Minte proposed a systematic study on the mechanical properties of membrane connections and the corresponding results have been incorporated into the German codes (Minite 1981). From above, most of them focused on the mechanical behaviors of membrane seams, in which the overlap seam has been studied deeply. There are lack of researches on other types of connections, for example, butt seam and membrane-edge connections, although they are of equal importance. As we know, coated fabric is nonlinear and viscoelastic, of which the mechanical properties is affected by temperature, humidity, and other environment factors (Bridgens 2004). Besides, the coating is the main connecting element in a seam, and can be influenced by temperature. Therefore, it is necessary to study the effects of temperature on the mechanical properties of membrane seams.

As shown in Table 1 (Gosling 2013, Bridgens 2012), a number of design guides have been developed in various countries, based on the allowable stress approach or a combined approach with a limit state check for overload conditions. The foregoing review of various codes and design guides has taken into account many different combinations of factors ranging from load conditions and structure size to pollution and life-cycle effects. The recommendations in Germany codes are

Table 1 Recommendations in current design codes or guides

Source	Stress factors	Stated uncertainty incorporated within the stress factor
Chinese technical specification CECS 158:2004	Partial coefficient 5.0 for load combination 1 2.5 for load combination 2	Load combination, uniaxial strength, connection Additional strength reduction factor for connection is 0.75.
IASS Working Group 7 recommendations	4.2 - 6.0 for warp 5.0 - 7.0 for weft.	Fabric and testing consistency; calculation accuracy; loading, fabrication and installation uncertainty; environmental degradation; unforeseen factors
French guides	4.5 - 7.0	Fabric and seam quality; structure scale (probability of defects); pollution & environmental degradation (including quality of finite element analysis)
DIN 4134	Fabric 4.9 - 6.4 permanent load 2.9 - 3.2 wind load 4.4 - 5.1 snow load Seams 6.7 - 9.5 permanent load 3.5 wind load 4.9 snow load	Uniaxial strength, modified depending on whether structure is loaded biaxially or uniaxially; load factor; material factor, accounting for seams and connections; load duration; pollution and degradation; temperature
Japan guides	8 for sustained loads 4 for temporary loads	No details provided
Italian code	4.5 wind 3.75 snow	For connections, three classes are defined, which account for different qualities of connection assemblies (manufactured or on site)
ASCE standard	4.0 - 7.8	Life cycle factor; strength reduction factor; load combination factor

more detailed, fully considering the effect of biaxial loading, temperature, connection, long-term loading, and others. IASS design guidelines present main factors that affect the resistance uncertainty, including material properties, geometry parameter and other factors, but do not provided details for connections. For Italian codes, for connections, three classes are defined which account for different qualities of connection assemblies. Chinese technical specification takes into account the effect of connection by incorporating the strength reduction factor. The other codes, for example, Japan and ASCE standard, do not provide the details for connections. From above, in current design guides or specifications for membrane structures, the corresponding strength reduction factor for connections has nothing to do with the types of connections as well as the failure modes of connections. However, it is known that the type of connections has significant effects on the load bearing capacity of connections. Therefore, it is necessary to study the mechanical properties of various types of connections in tensioned membrane structures. A better understanding of the mechanical behaviors of membrane connections may significantly increase the confidence and reduction in uncertainty (Galliot 2009, Pargana 2007).

This paper aims to present the mechanical properties of membrane connections in tensioned membrane structure, including membrane seams, membrane-flexible edge connections and

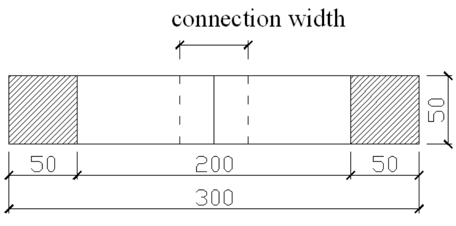


Fig. 4 Dimension of butt seam

membrane-rigid edge connections. The failure modes of different connections are studied and the corresponding strength factors are proposed. The results can be references for the design and analysis of membrane structures.

2. Experiment

The butt seams of PVC coated fabric including welded seam and glued seam are taken as the research object. According to DIN 53354, the length of sample is 300±1 mm, the width is 50±0.5 mm and the length of gripped end is 50mm. In order to compare with the material tensile strength, the dimensions of seam specimen are the same as the material specimen. The connection widths are 20mm, 50mm and 80mm, respectively. The pattern equality of samples is important for the test results. The uniaxial tests are carried out using the electromechanical universal testing machine with temperature box. According to the current design specifications and usual application environments, 70℃ and −20℃ is chosen as the high-temperature and low-temperature (Foster 2004). The test temperatures are −20℃, −10℃, 0℃, 10℃, 23℃, 40℃, 50℃, 60℃ and 70℃, respectively. For each test, at least five samples are tested. The samples and jigs must be put at the testing temperature for at least one hour before testing.

In actual engineering, the membrane-flexible edge connection is always the connection of membrane and cable. As shown in the reference (Zhang 2012), the boundary fasteners used in the membrane roof of Shanghai EXPO are presented. In the inner low points of sun valleys where the load peaks concentrate, the designers proposed a double-layered construction and considered excess tensions in the analysis. Besides, the usual boundary fasteners can not satisfy the requirement of the design. Therefore, seven types of fasteners are designed to be conducted in the tests, as shown in Fig. 5. Among them, fasteners F1 and F2 are made by steel and the others are made by aluminum. The effects of the types and sizes of the fasteners as well as the loading ways on fastener performance are studied

As mentioned above, the clamp plate connection is popular in the connections of membrane and rigid edge. It is always used to join large prefabricated membrane panels together, and can be installed on site with a strong visual appearance. It is always used for subdividing very large fabric fields to ease handling in the shop. The dimensions and test setup of the clamp plate connection are shown in Fig. 6. The specimen is with the length of 600mm and the width of 200mm. The orthogonal test is to analyze the test results with different connection parameters, as shown in Table 2. According to experience, six parameters are chosen in the L18 (21×37) orthogonal table, including bolt distance, keder diameter, plate thickness, plate width, composite edge width, and type of pocket (Li 2004). Two specimens are conducted for each group.

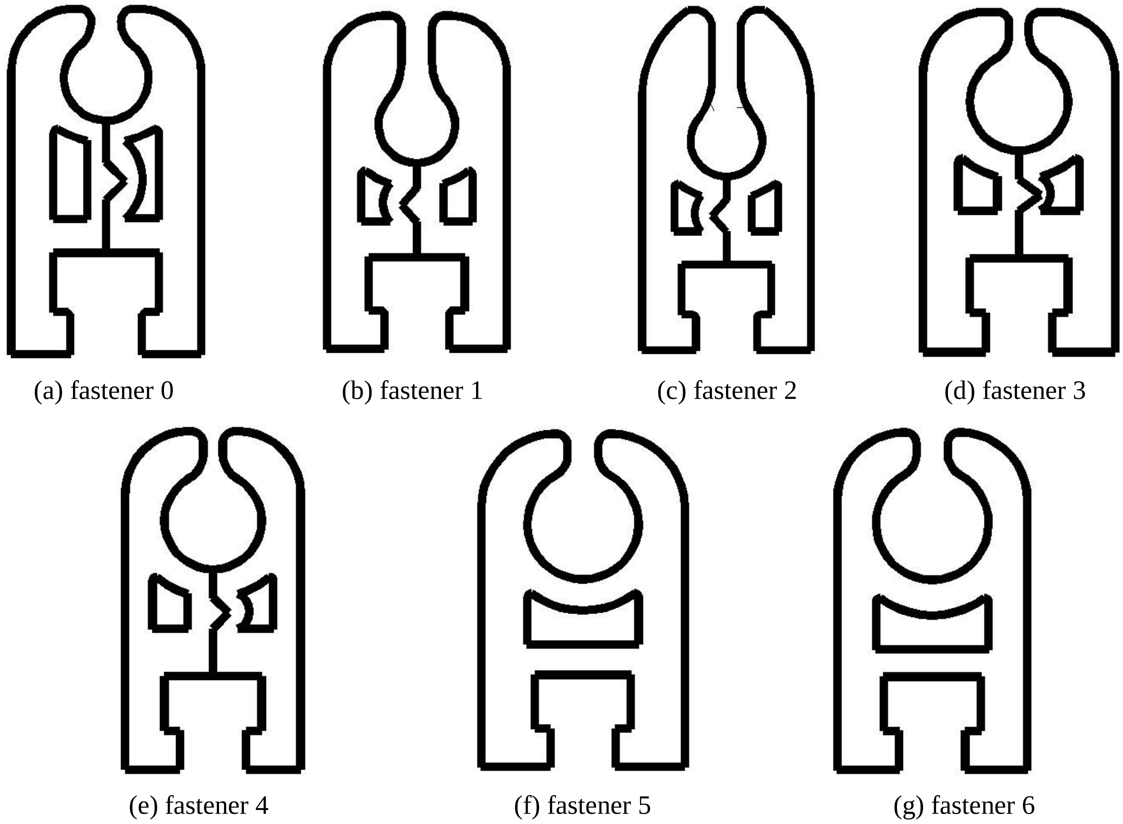


Fig. 5 Boundary fasteners

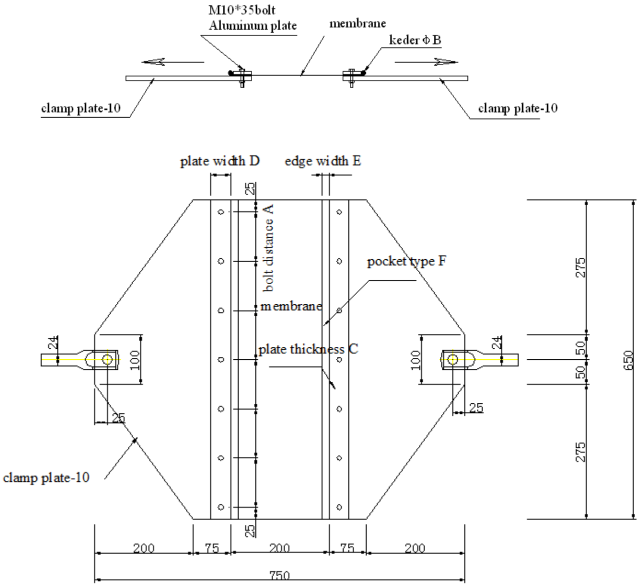
Table 2 Orthogonal table for the clamp plate connection

Parameter	Bolt distance A (mm)	Keder diameter B(mm)	Plate thickness C(mm)	Plate width D(mm)	Composite edge width E(mm)	Type of pocket F
1	100	4	4	40	10	Welded
2	150	8	6	50	20	Glued
3	200	12	8	60	30	——

3. Results and discussions

3.1 Membrane seams

From the test results, the seam strength strongly depends on the failure mode of seams. The failure modes of butt seams are shown in Fig. 7. In the tests of welded seams, three typical failures are observed including seam failure, welded layer slippage, and fibers pulled-out. In the tests of glued seams, three typical failures are observed including seam failure, degumming, and mixed failure. When the bonding to the weave is not enough strong, the coating will come loose from the fabric. It is called as "adhesion failure", degumming for glued connection and welded layer slippage for welded connection. When the weave itself loses its connectivity compounded the



Dimensions of clamp plate connection

Test setup

Fig. 6 Test of clamp plate connection

Seam or adjacent membrane failure

Welded layer slippage

Fibers pulled-out

Seam or adjacent membrane failure

Degumming

Mixed failure

Fig. 7 Failure modes of butt seams

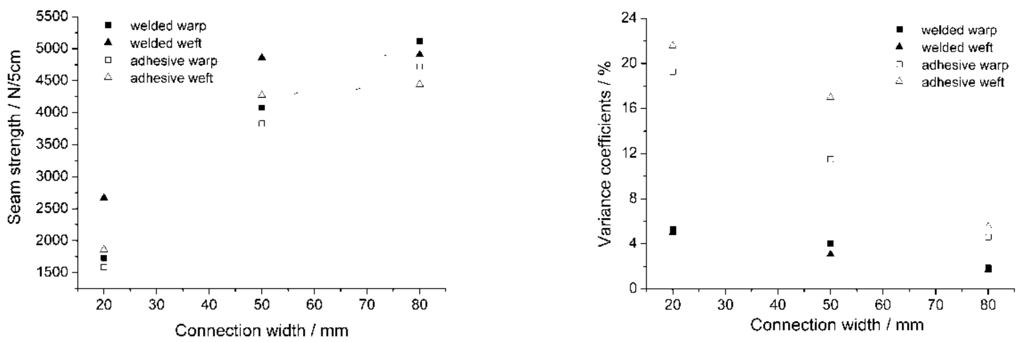
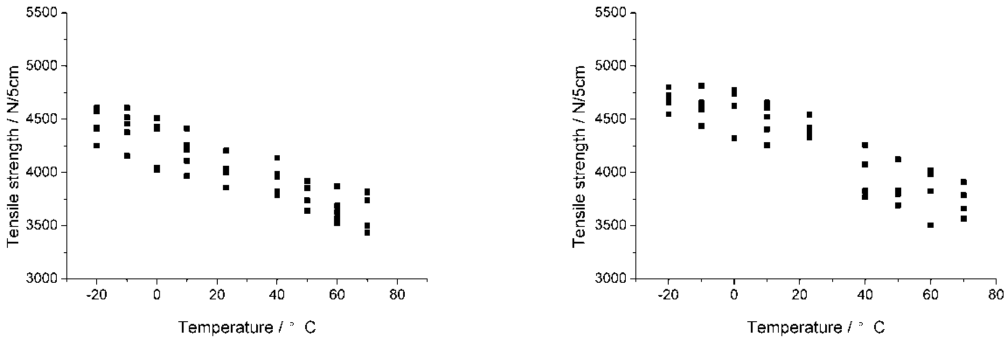


Fig. 8 Test results of butt seams



Warp Weft

Fig. 9 Dependence of test temperature on seam strength

effect of coating, it is called as “mixed failure”. The expected failure is type 1, seam failure or adjacent membrane failure, because close to the seam the stresses in the fabric are doubled, which is called as “stress singularity”.

As shown in Fig. 8, with connection width increasing, the strength of seam increases and the variability of test results decrease. When the connection width is 20 mm, the failure mode of welded seam is always welded layer slippage or fibers pulled-out. For weft samples, when the connection width is 50 mm, it can achieve the maximum value of seam strength. Then, 50 mm can be considered as the optimum width and the failure mode is seam failure. For warp samples, the optimum width is 80 mm and then the failure mode is fibers pulled-out. This is because the prestress of weft fibers is lower and the friction between weft and warp fibers is lower, the warp fibers are easily pulled-out. The effect of connection width on the strength of glued seams is similar to that of welded seams. The strength of welded seams can achieve 90% of the membrane strength, while the strength of glued seam can achieve 80% of the membrane strength.

The effect of temperature on the tensile strength of butt welded seams is shown in Fig. 9. Results show the temperature has significant effects on the seam strength. The seam strength decreases and the strain at break remains almost unchanged with temperature increasing, which is in consistent with the variation of membrane strength. The failure modes under different temperatures are the same as that under room temperature.

Table 3 Tensile strength of butt welded seams at −20℃, 23℃ and 70℃

Type	Specimen direction	Tensile strength / kN/m						Temperature Influence factor	
		23℃		70℃		-20℃			
		Average value	5% Fractile	Average value	5% Fractile	Average value	5% Fractile	High	Low
Seam	Warp	101.06	99.51	90.86	83.06	110.76	105.16	1.112	1.096
	Weft	109.14	104.59	92.68	89.56	118.05	112.40	1.178	1.082

Table 4 The ratio of seam strength to membrane strength under different temperatures

Direction	Strength ratio (seam strength / membrane strength)								
	−20℃	−10℃	0℃	10℃	23℃	40℃	50℃	60℃	70℃
Warp	0.91	0.94	0.92	0.91	0.93	0.91	0.92	0.91	0.92
weft	0.93	0.92	0.94	0.93	0.94	0.92	0.92	0.91	0.91

The temperature influence factors for membrane seam can be calculated as follows according to literature 1.

High-temperature influence factor：
$$\gamma_1 = \frac{f_1}{f_2} \tag{1}$$

Low-temperature influence factor：
$$\gamma_2 = \frac{f_3}{f_2} \tag{2}$$

Where, f_1, f_2, f_3 are the average tensile strength of 70℃, 23℃ and −20℃, respectively.

Table 3 shows the test results of butt welded seams at −20℃, 23℃ and 70℃. The temperature reduction factor γ for this material is 1.112 (high) and 1.096 (low) in warp, while the high temperature reduction factor γ for this material is 1.178 (high) and 1.1082 (low) in weft.

The ratio of seam strength to membrane strength is got by dividing the seam strength by the membrane strength. It is am important index to evaluate the safety reliability of membrane seams. As shown in Table 4, with proper processed, the seam strength can achieve 90% of the membrane strength under test temperatures.

3.2 Membrane-flexible edge connection

Fig. 10 shows the failure modes of membrane-flexible edge connections. For type 1 named “failure of membrane”, the failure always appears when the strength of welding is no less than the strength of material, due to good process equality. For type 2 named “failure of welding”, the failure appears in the welding part. For type 3 named “failure of membrane pocket”, the failure always appears in membrane pocket, because of poor processed equality or stress concentration due to uneven deformation. For type 4 named “rope pulled out”, the rope is drawn out from the boundary fastener, due to low constraint of boundary fastener. It's worth noting that, in many countries, the rubber bead (“keder”) is used to avoid the problem.

Table 5 shows the test results of boundary fasteners. During the tests, the results under vertical loading show that F2 (Fastener 2 is abbreviated as F2) does not meet the requirements, so it is unnecessary to carry out the tests under inclined loading. Due to lack of constraint, F0 is suitable

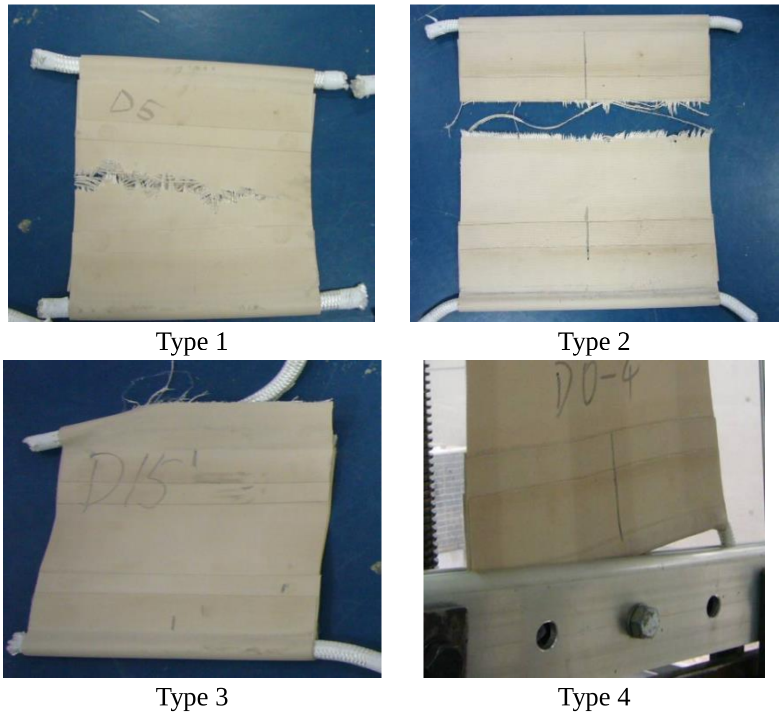


Fig. 10 Failure modes of membrane-flexible edge connections

for the single-layer membrane, but not for the double-layer membrane. During the tests of F1, the main failure mode is type3, because the constraint of boundary fastener is too strong. For fastener F2, the failure mode is type4, due to weak constraint of boundary fastener. For fasteners made by steel (F1, F2), the boundary constraint is so strong that the unexpected failure modes happen and the corresponding load bearing capacity is lower than expectations. Therefore, the boundary fasteners made by steel can not meet the requirements. For fasteners made by aluminum (F3~F6), the test results are relatively well, except some examples with poor processing equality. Then, the main failure mode is type 1, and the other is type 2, which meets the expectations of the design. The measured tensile strength is no less than the material tensile strength. Finally, after comprehensive consideration, fastener F5 made by aluminum is chosen as the boundary fastener in the actual engineering. Results show with proper fastener, the strength of membrane welding can achieve 90% of the material strength, which is in consistent with the design requirements.

3.3 Membrane-rigid edge connections

3.3.1 Failure mode

The failure modes of clamp plate connections are summarized as listed in Table 6 and Fig. 11. The failure always happens in one side of the membrane pocket and propagates quickly along the edge. Fig. 11 (a) and (b) shows the failure mode of the clamp plate connections with welded pocket. In the initial phase, the load is carried by the friction created between clamp plate and membrane, and then it is approximately uniform. When the load increases, in the areas away from the bolts, after the friction between clamp plate and membrane is overcome, the force is mainly

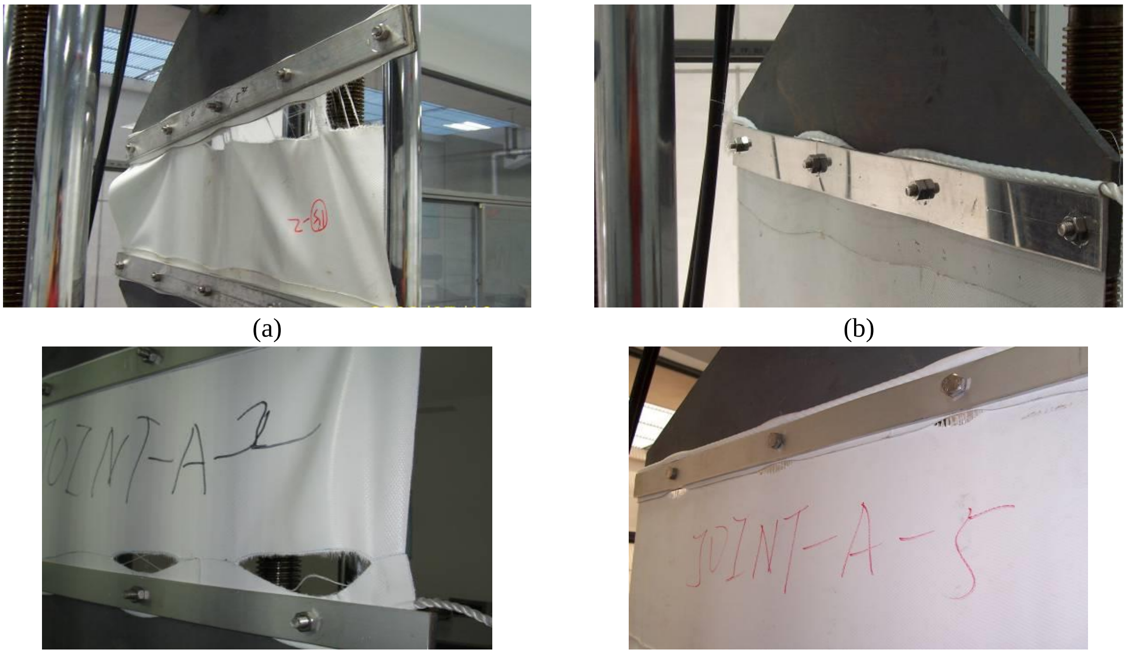
Table 5 Test results of boundary fasteners

Type	Loading protocol	Single layer membrane		Double-layer membrane	
		Failure load kN	Failure mode	Failure load kN	Failure mode
F0	vertical	53.60	1	75.50	4
		49.95	1	68.35	4
		50.90	1	73.95	3
	inclined	49.55	4	75.70	4
		53.85	1	72.65	4
		51.50	1	70.60	1
F1	vertical	46.90	3	89.95	1
		42.75	3	88.10	3
		43.55	3	90.50	3
	inclined	54.50	1	89.55	1
		48.15	1	89.65	1
		50.80	1	92.30	1
F2	vertical	25.66	4	42.65	4
		24.58	4	47.05	4
		20.64	4	42.50	4
F3	vertical	47.45	1	83.85	1
		50.35	1	86.45	1
		53.00	1	77.00	1
	inclined	47.05	1	83.65	3
		49.35	1	86.45	1
		52.15	1	87.25	1
F4	vertical	48.45	1	84.45	1
		50.70	1	86.95	1
		45.95	1	73.20	3
	inclined	44.25	2	79.50	1
		42.85	1	84.35	1
		45.65	1	71.85	3
F5	vertical	50.10	1	89.70	1
		52.15	1	87.50	1
		46.25	1	92.30	1
	inclined	44.00	1	72.31	1
		40.85	1	70.18	3
		42.33	1	72.12	1
F6	vertical	54.85	1	83.35	1
		50.60	2	91.80	1
		50.65	1	79.00	1
	inclined	50.55	1	74.10	1
		48.15	1	81.05	1
		54.05	1	75.21	1

carried by the compression between the keder and clamp plate. In the area close to the bolts, the force is still carried by the friction. Finally, in the areas away from the bolts, slippage appears between clamp plate and membrane and the keder is easily compressed into the gap of plates, as shown in Fig. 11(b). The uneven deformation leads to stress redistribution and the membrane

Table 6 Failure modes of the membrane-rigid edge connection

Failure type	Description of failure mode			Connection strength kN/m
	Keder compressed into the plate gap	Visible deformation of clamp plate	Failure of membrane pocket	
1	No	No	Yes	71.84
2	No	Yes	Yes	64.18
3	Yes	Yes	Yes	56.53



(a) (b) (c) (d)

Fig. 11 Failure modes of the membrane-rigid edge connection

stress near the bolts is higher than the other parts. Then, the membrane pockets near the bolts fail because of the stress concentration and the fiber damage due to the holes, as shown in Fig. 11(c). In the initial of the tests, the load transmission of the clamp plate connections with glued pockets is similar to that of the connections with welded pockets. In the final of the tests, slippage appears between clamp plate and membrane in the areas away from the bolts and then the adhesion failure of pocket may lead to the degumming, as shown in Fig. 11(d). This is the difference between the two types of connections.

From the test results, the failure strength of connections has strong correlation with the failure modes of connections. The average connection strengths corresponding to different types of failure are 71.84 kN/m, 64.18kN/m and 56.53kN/m, respectively. The tensile strength corresponding to failure type 1 is the highest and the tensile strength corresponding to failure type 3 is the lowest, which is about 50% of the membrane strength. By experience, the expected failure is type 1, and then the connections can transfer the force effectively. The failure of type 3 and type 2 should be prohibited in the design. The transmission of load between the membrane and the edge occurs by the keder bearing against the edge and the friction between the membrane and the edge. In these connections, larger bolt distance and thinner keder will lead to the keder easily compressed into the plate gap and enlarge the uneven deformation of specimen. For clamp plate connection with glued pockets, degumming will enlarge the uneven deformation and it may accelerate the failure of connections. The variation coefficients of welded pocket connections are lower than that of glued pocket connections. This is consistent with the test results of membrane seams. From above, the connection parameters have significant effects on the mechanical properties of connections. It is necessary to choose proper parameters to ensure the performances of connections.

3.3.2 Parameter analysis

Proper design and analysis of fabric structures require a fundamental understanding of the connection behaviors. The variance analysis is used to analyze the effects of parameters on the connection performances, in order to propose proper connection parameters for the design. In the variance analysis of orthogonal tests, the F test is used to determine the significance of various factors. The basic approach is to constitute the square sum of deviation due to influence factors and the square sum of the deviation due to test error to the statistic value F (Jay 2005).

The results of orthogonal tests are listed in Table 7. Where, $K_i = \sum_{j=1}^{n} Y_{i,j}$ is the sum of test results of level i, and $\overline{K_i} = \sum_{j=1}^{n} Y_{i,j} / n$ is the average value, and $T_i = \sum_{j=1}^{n} Y_{i,j}$ is the sum of level i.

Given the significance level α, the critical value F_α can be found from the distribution table. Then, compare F with $F_\alpha(\upsilon_F, \upsilon_e)$ to justify the significances as follows.

When α =0.10, if $F > F_{0.1}(\upsilon_F, \upsilon_e)$, ”*” is marked in the variance table.

When α =0.05, if $F > F_{0.05}(\upsilon_F, \upsilon_e)$, ”**” is marked in the variance table.

When α =0.01, if $F > F_{0.01}(\upsilon_F, \upsilon_e)$, ”***” is marked in the variance table.

The results of variance analysis for orthogonal tests test are shown in Table 8. Where, e_1 is the deviation due to influence factors and e_2 is the deviation due to test error. It can be seen that the most important factor that affecting the connection strength is bolt distance. The bolt distance is related to the out-of-plane stiffness of the clamp plates. If the bolt distance is smaller, lower stiffness of clamp plate is needed, which is related with the plate thickness C and the plate width D. The keder diameter should be proper to avoid the keder compressed into the plate. Besides, the keder needs to be held continuously along its full length. Further, the membrane pocket should be strong enough to avoid the pocket failure ahead. The type of membrane pocket, glued pocket or welded pocket, has slightly effects on the connection strength. However, the welded pocket is recommended in the design, because the variability of welded pocket is less than that of glued pocket. These conclusions are also applicable for the clamp plate connection used in the membrane-flexible edge connections.

The dependence of connection strength and failure mode on connection parameter is shown in Fig. 12. As mentioned above, the expected failure mode is type 1, of which the connection strength is the highest. When the bolt distance is 200mm, the plate thickness is 4mm or the keder diameter is 4mm, it went against the load transmission of connections. The main failure mode is type 3 and the probability is about 50%. Moreover, the expected failure mode type 1 can hardly happen. Therefore, this type of connection parameters should be avoided in the design. With the bolt

Table 7 Results of orthogonal tests

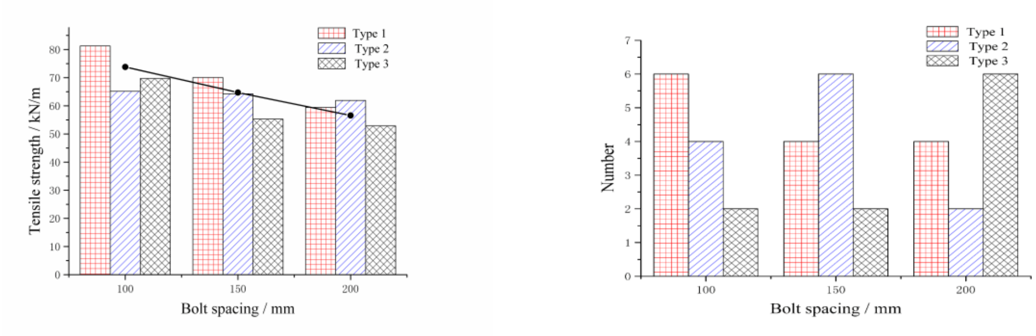
Number	Factor						Connection strength kN/m		T_i
	A (1)	B (2)	C (3)	D (4)	E (5)	F (6)	Sample 1	Sample 2	
1	1(100)	1(4)	1(4)	1(40)	1(10)	1(welded)	76.77	58.54	135.31
2	1	2(8)	2(6)	2(50)	2(20)	1	64.00	61.31	125.31
3	1	3(12)	3(8)	3(60)	3(30)	1	88.08	76.23	164.31
4	2(150)	1	2	3	3	1	68.54	65.15	133.69
5	2	2	3	1	1	1	62.92	67.23	130.15
6	2	3	1	2	2	1	69.15	53.88	123.03
7	3(200)	2	1	2	3	1	51.05	55.35	106.40
8	3	3	2	3	1	1	66.38	54.15	120.54
9	3	1	3	1	2	1	58.23	58.92	117.15
10	1	3	3	2	1	2(glued)	79.46	71.92	151.38
11	1	1	1	3	2	2	68.46	68.92	137.38
12	1	2	2	1	3	2	83.08	88.92	172.00
13	2	2	3	3	2	2	79.15	71.08	150.23
14	2	3	1	1	3	2	68.69	60.31	129.00
15	2	1	2	2	1	2	56.77	53.82	110.58
16	3	3	2	1	2	2	60.00	63.85	123.85
17	3	1	3	2	3	2	53.31	58.15	111.46
18	3	2	1	3	1	2	46.40	53.08	99.48
$\boldsymbol{K}_1$	885.69	745.58	730.60	807.46	747.45	1155.89	1200.45	1140.82	2341.26
$\boldsymbol{K}_2$	776.69	783.57	785.97	728.17	776.95	1185.37			
$\boldsymbol{K}_3$	678.88	812.11	824.69	805.63	816.86	——			
$\overline{\boldsymbol{K}}_1$	73.81	62.13	60.88	67.29	62.29	64.22			
$\overline{\boldsymbol{K}}_2$	64.72	65.30	65.50	60.68	64.75	65.85			
$\overline{\boldsymbol{K}}_3$	56.57	67.68	68.72	67.14	68.07	——			

Table 8 Variance analysis of orthogonal tests

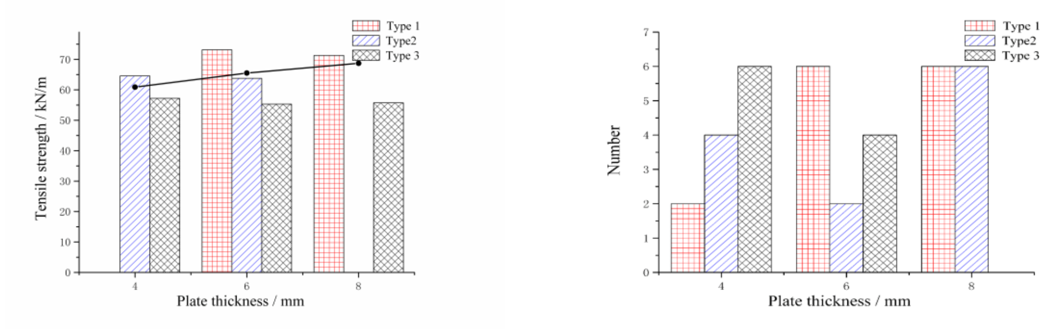
Variance source	Square sum of variance $\boldsymbol{S}$	Degree of freedom v	Mean variance $\boldsymbol{V}$	F value	Significance
A	1783.93	2	891.96	24.28	* * *
B	185.63	2	92.82	2.53	
C	372.73	2	186.37	5.07	* *
D	341.42	2	170.71	4.65	* *
E	202.27	2	101.14	2.75	*
F	24.14	1	24.14	0.66	
Deviation $\boldsymbol{e}_1$	328.43	6	54.74		
Deviation $\boldsymbol{e}_2$	516.47	17	30.38		
Deviation sum	844.90	23	36.73		
Sum	3755.03	34			
$F_{0.01}(2, 23)=7.88$, $F_{0.05}(2, 23)=3.42$, $F_{0.1}(2, 23)=2.55$					

Table 9 Test results of connections with proper connection parameters

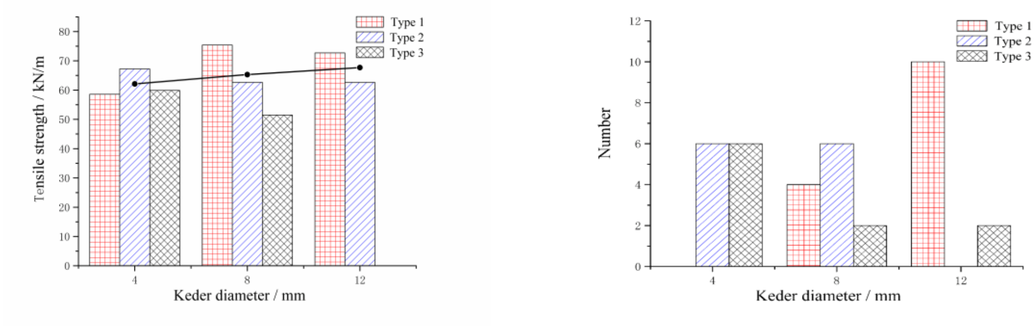
Test number	Connection parameter						Connection strength (kN/m)	
	Bolt distance (mm)	Keder diameter (mm)	Plate thickness (mm)	Plate width (mm)	Edge width (mm)	Pocket type	1	2
3	100	12	8	60	30	Weld	88.08	76.23
5	150	8	8	40	10	Weld	62.92	67.23
10	100	12	8	50	10	Glued	79.46	71.92
12	100	8	6	40	30	Glued	83.08	88.92
13	150	8	8	60	20	Glued	79.15	71.08
Average value							76.81	



(a) Bolt distance (b)



(a) Plate thickness (b)



(a) Keder diameter (b)

Fig. 12 Connection properties and failure modes with different parameters distance decreasing, the plate thickness and the keder diameter increasing, the connection strength increases and the failure mode of connections changes from type3 to type1. When the bolt distance is 100mm, the plate thickness is 8mm and the keder diameter is 12mm, it is conductive to the load transmission of connections. Then, the main failure mode with the probability of 50% is type 1, while the type 3 failure can hardly happen. From above, the effects of the connection parameters on the connection behaviors including failure strength and modes are obvious. It can be concluded that with proper connection parameters, the connection strength of membrane-rigid edge connection can achieve 75% of the membrane strength. Five groups of test results with proper parameters are summarized in Table 9, which can be references for the design and analysis of membrane structures.

4. Conclusions

This paper presents the tests of three types of membrane connections used in tensioned membrane structures and proposes the corresponding strength reduction factors for the design. The following conclusions are drawn out, which can be references for the design and analysis of membrane structures.

The seam strength strongly depends on the failure mode and the connection width of seams. With connection width increasing, the strength of membrane seam increases and the variability of test results decrease. In the tests of welded seams, three typical failures are observed including seam failure, welded layer slippage, and fibers pulled-out. In the tests of glued seams, three typical failures are observed including seam failure, degumming, and mixture failure. The expected failure is membrane failure close to the seam, due to stress singularity. With proper processed, the strength of welded seams can achieve 90% of the membrane strength and the strength of glued seam can achieve 80% of the membrane strength. The strength of welded seams is close to that of glued seams, but the variability of tests results for glued seams is worse than that of welded seams. The effect of temperature on the strength of welded seam is obvious. With temperature increasing, the strength of weld seams decreases and the seam strength can achieve more than 90% of the membrane strength under test temperatures.

In the tests of membrane-flexible connections, the effect of the material and dimensions of boundary fasteners on the connection strength is obvious. For fasteners made by steel, the boundary constraint is so strong that the failure mode is rope pulled-out or failure of membrane pocket, and the load bearing capacity is lower than expectations. For fasteners made by aluminum, the test results are relatively well than those made by steel. Four types of failure modes are observed, including membrane failure, welding failure, membrane pocket failure, and rope pulled out. Most of the failure mode is failure of seam or adjacent membrane, which is consistent with the expectations of the design. The connection strength is no less than the material tensile strength. With proper processed, the strength of membrane-flexible edge connection can achieve 90% of the material strength.

In the tests of membrane-rigid edge connections, proper failure mode should be failure of membrane adjacent to the pocket. The uneven deformation created during the tests leads to the stress concentration near the bolts and the pocket edge. The transmission of load between the membrane and the edge occurs by the keder bearing against the edge of the clamp plates and the friction between membrane and clamp plate. From the results of orthogonal tests, it can be concluded that the importance sequence of influence factor is bolt distance, plate thickness, plate width, edge width, keder diameter, and pocket type. Finally, proper connection parameters are proposed for the design. With proper connection parameters, the connection strength of membrane-rigid edge connection can achieve 75% of the membrane strength.

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References

Bridgens, B.N. and Gosling, P.D. (2004), “Direct stress-strain representation for coated woven fabrics”, *Comput. Struct.*, **82**, 1913-1927.

Bridgens, B.N. and Birchall, M. (2012), “Form and function: the significance of material properties in the design of tensile fabric structures”, *Eng. Struct.*, **44**, 1-12.

Chen, W.J., Tang, Y.F., Zhao, D.P., Ren, X.Q., Fu, G.Y., Dong, S.L. (2007), “Experiments on the mechanical properties and the welded seam properties of architectural membranes”, *Spatial Struct.*, **3**(1), 37-44. (in Chinese)

DIN 53354 (1981), Testing of Artificial Leather-Tensile Test.

Forster, B. and Mollaert, M. (2004), *European Design Guide for Tensile Surface Structures*, TensiNet.

Galliot, C. and Luchsinger, R.H. (2009), “A simple model describing the non-linear biaxial tensile behaviour of PVC-coated polyester fabrics for use in finite element analysis”, *Comput. Struct.*, **90**, 438-447.

Gosling, P.D., Bridgens, B.D. and Zhang, L. (2013), “Adoption of a reliability approach for membrane structure analysis”, *Struct. Saf.*, **40**, 39-50.

Kim, H.K. and Kawabata, M. (2005), “Study on stress transition mechanism of clamping part of membrane structures-tensile and fracture characteristics of membrane material in bolting part”, *Research Report on Membrane Structures 2005*, The Membrane Structures Association of Japan, 41-48.

Devore, J.L. (2005), *Probability and statistics for engineering and the sciences*, The 6th edition, Beijing, China Machine Press.

Skelton, J. (1971), “The seaming of lightweight coated fabrics”, *J. Indus. Text.*, **1**, 86-100.

Yang, L. (2007), *Study and applications on mechanical properties of membrane materials and structures, Shanghai*, Tongji University. (in Chinese)

Minte, J. (1981), *Das mechanische Verhalten von Verbindungen beschichteter Chemiefasergewebe*, RWTH Aachen, Diss.

Pargana, J.B., Lloyd-Smith, D. and Izzuddin, B.A. (2007), “Advanced material model for coated fabrics used in tensioned fabric structures”, *Eng. Struct.*, **29**, 1323-1336.

Zhang, Y.Y., Zhang, Q.L. and Yang, Z.L. (2012), “Experimental and theoretical analysis of membrane structure based on the load-dependent constitutive relations”, *Proceedings of IASS 2012 Annual Symposium*, **38**(8), 38-40.