IMPROVEMENT ON TENSILE STRENGTH AND FATIGUE PERFORMANCES OF MESHED GUM METAL PLATES FOR BONE GRAFT APPLICATIONS

Koki SEKIGUCHI, Jianmei HE

Kogakuin University, Department of Mechanical Engineering, Tokyo, Japan
e-mail: Am16040@ns.kogakuin.ac.jp

Abstract: Degenerative intervertebral discs have a sign of epidemic as one of diseases caused by aging and lifestyle habits. Currently practiced treatments called spinal fusion surgery using pure titanium or titanium alloy implant products have the problems like overloading on healthy nature bones caused by the extra stiffness and heavy weight of such metal implants. Therefore, creation of implant products that meets mechanism like density, elasticity/rigidity of nature bones are required to reduce the burden on patient's health bones. Meshed titanium plates for bone graft applications have improved with excellent three-dimensional (3D) flexibility, lower elastic modulus and higher strength in previous studies. In this study, mesh structures as applied on Gum Metal plates with high biocompatibility are interested and their tensile strength/fatigue performance are investigated through analytical and experimental approaches for implant application on intervertebral disc defections. Based on different basic mesh shapes designed in this study, sample meshed Gum Metal plates were fabricated by laser cutting process and tensile fatigue experiments were executed. It concluded that high strength and fatigue performance of meshed Gum Metal plates can be obtained by using with some kind of designed basic mesh shapes.

Keywords: Tensile Strength, Fatigue Performance, Mesh Structure, Gum Metal Plates, Analytical and Experimental Approaches

Introduction

Recently in Japan, degenerative intervertebral discs have a sign of epidemic as one of diseases caused by aging and lifestyle habits. Degenerative intervertebral discs include lumber disc herniation, intervertebral disc herniation and cervical disc herniation. Table 1 shows the comparison of annual case numbers of these patients with/without surgeries having been increased year by year.

Table 1: Comparison of annual case number of surgeries for hernia of intervertebral discs

Individual surgeries	Total case number		Average days in hospital	
Accumulation period	2014.4～2015.3	2016.4～2017.3	2014.4～2015.3	2016.4～2017.3
Surgical removal	7,152	8,216	11.5	10.6
Other surgeries	17,187	17,156	18.0	17.3
No surgeries	16,590	17,246	9.8	9.9
Total throughout the year	40,929	42,618	13.5	13.0

In this study, disc herniation as one type of disc defects is interested. Disc herniation means that the intervertebral disc protrudes beyond the normal intervertebral space to compress the nerve and cause pain as shown in Fig.1. The treatment for disc herniation varies depending on different conditions. One of the currently practiced treatments is called spinal fusion surgery using metallic implants as also shown in Fig. 1. In this treatment, the upper and lower spinal cords of the defective disc are fixed using pure titanium or titanium alloy implant products. However, there is a problem that the loads caused by the titanium metal implants on the nature bones of the human body are large and will cause overloading on healthy nature bones[1]. Therefore, in order to reduce the loads on patient's health bones, creation of flexible implant products matching the mechanism such as the elasticity and rigidity of natural bones are desired as much as possible.

Mesh structure[2] applications are then considered for Gum Metal plates as applied on spine for hernia of intervertebral discs. Basic mesh shapes are designed and applied for Gum Metal plates and mechanical performances such as bending stiffness, tensile strength and fatigue performances of such meshed Gum Metal plates are experimentally and analytically evaluated[3]~[6]. The purpose of this study is to improve the tensile strength and fatigue performances of meshed Gum Metal plates as applied for hernia of intervertebral discs.

Fig. 1 MRI image of disc herniation (left) and metallic implant installation examples (right)

Design of Basic Mesh Shapes for Meshed Gum Metal Plates

Mechanical characteristics of Gum Metal plates

As shown in Fig. 2, Gum Metal material shows characteristics like relatively low elasticity rigidity, high strength, large elastic deformability and high biocompatibility compared with other metals and metal alloys.

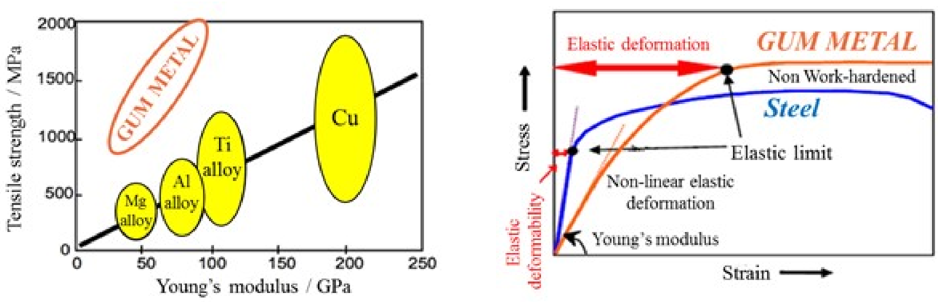

Fig. 2 Comparison of mechanical properties between GUM METAL and other metals

Designed basic mesh shapes and model of meshed Gum Metal plates

Basic mesh shapes are designed under the following design conceptions.

(1) Single fundamental mesh shape construction for simplification of manufacturing processing and cost-down purpose
(2) Higher three-dimensional flexibilities including expansion/contraction, bending and torsion for possibility of handily shape changes during surgery
(3) Easy-controllable mechanical properties like elastic modulus, bending stiffness etc. for approachability to natural-bone's mechanical properties

Fig. 3 shows an example of the meshed structure with S curves obtained by patterning the basic mesh shape following the above design concepts.

Fig. 3 Example of meshed structure with S curves from basic mesh shape pattern

Two types of basic mesh shapes are designed based from regular tetragon and regular hexagon, 90° and 60° axisymmetric mesh shapes, following the above mentioned design concepts using 3D CAD software SolidWorks as shown in Fig. 4. The radius *R* and diameter *D* of the circles shown in Fig. 4 are taken as design variables of basic mesh shapes for parametric studies. For each types, basic mesh shapes are introduced for analytical and experimental approaches having different design variables and including the improved mesh designs of 90° axisymmetric 90°-④ and 90°-⑤ as shown in Fig. 5. Using these basic mesh shapes, prototype meshed plate models of meshed plates are then created and also shown in Fig. 5. Meshed Gum Metal plate specimens are then manufactured by laser-cutting processing as shown in Fig. 6. These meshed plate specimens are subjected to tensile fatigue experiments to evaluate their tensile fatigue characteristics and shape models are used for stress analysis. The influence on the stress concentration of the meshed plate specimens by different design parameters are evaluated by finite element analysis through ANSYS Workbench.

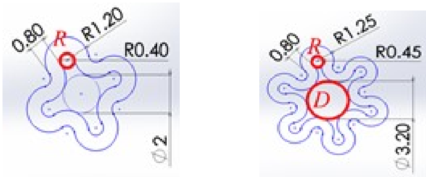

Fig. 4 Design variables of basic mesh shapes (left: 90° axisymmetric type, right: 60° axisymmetric type)

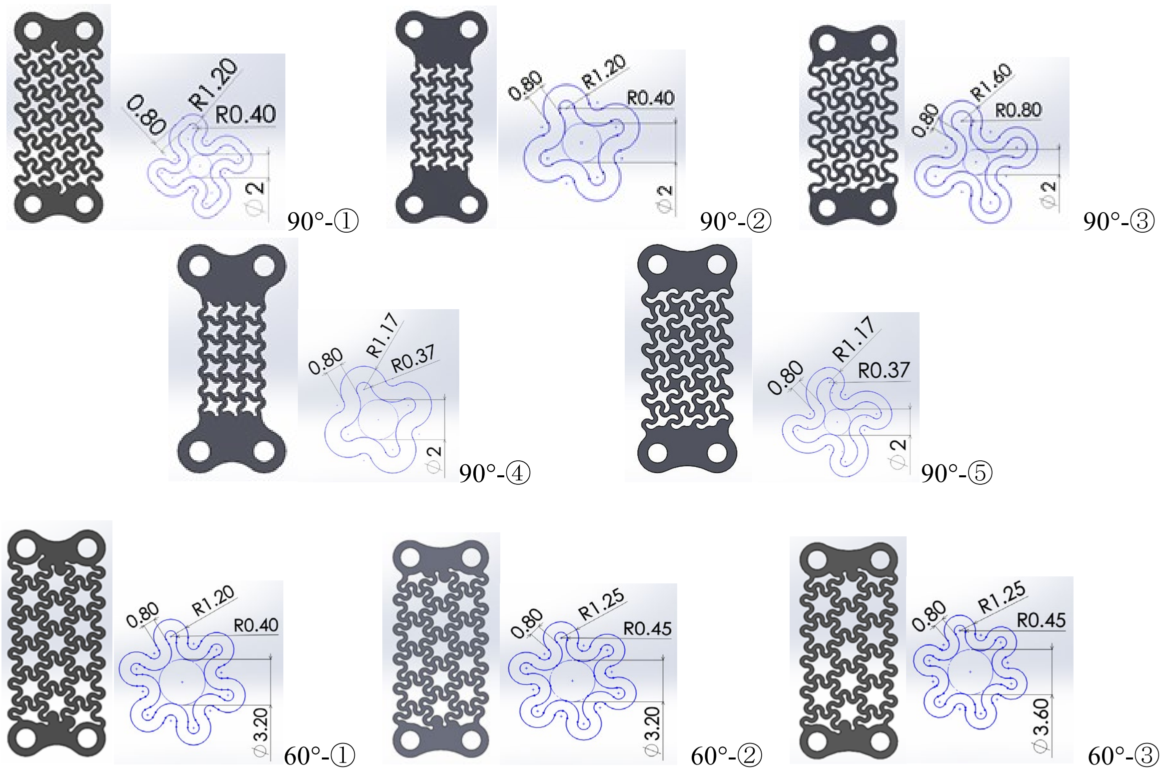

Fig. 5 Basic mesh shapes and meshed plate models for meshed Gum Metal plate specimens
(90° axisymmetric shapes: ①-⑤, 60° axisymmetric shapes: ①-③)

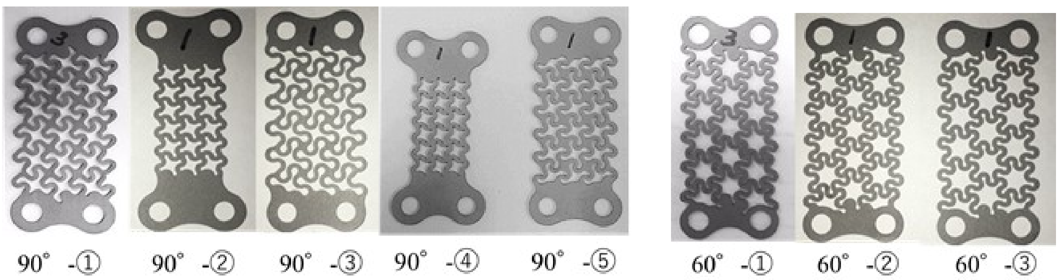

Fig. 6 Sample meshed Gum Metal plate specimens for tensile fatigue tests
(left: 90° axisymmetric shapes ①-⑤, right: 60° axisymmetric shapes ①-③)

Tensile Fatigue Characteristics of Meshed Gum Metal Plates

Tensile fatigue experiment on meshed Gum Metal plates

Tensile fatigue tests of meshed Gum Metal plate specimens were conducted based on JIS standard Z 2273 using special fixtures necessary for thin plates. Total 36 specimens of 6 types of meshed plates were tested with testing machine (Asahi Seisakusho FRS-20) and specimen installation as shown in Fig. 7. The amplitude of iterated tensile loads were ranged from 20N to 90N with 10N amplify and 5N minimum tensile loading as shown in Table 1. The frequency of tensile load iteration was set at 10Hz.

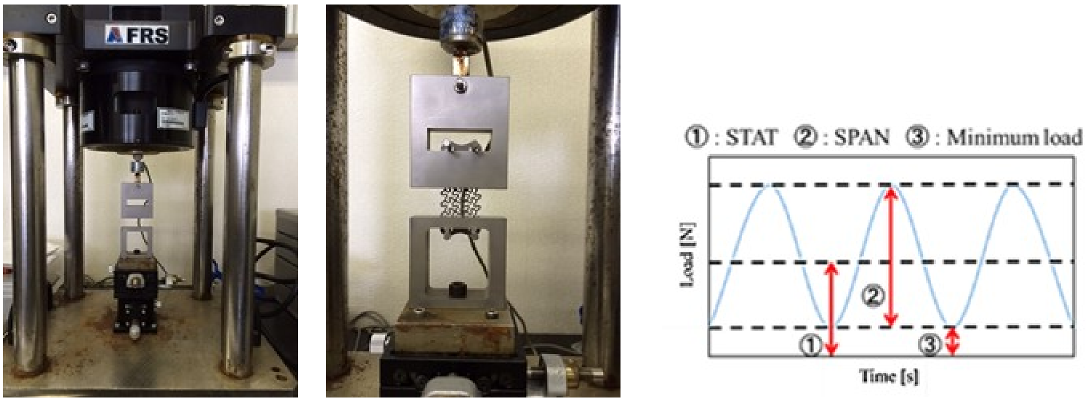

Fig. 7 Tensile fatigue experiment and meshed Gum Metal plate specimens with machine, fixtures and settings

Table 1 Tensile fatigue test tensile loads (90° and 60° axisymmetric specimens)

No. of specimen	No.1~No.6
SPAN [Np-p]	20N~90N
STAT [N]	25N~95N
FREQ [Hz]	10.0

Stress analysis for meshed Gum Metal plates under fatigue tensile loading

It is difficult to use the effective cross-sectional area of the meshed plate specimens for stress calculations because of the complex meshed shapes. Then stress analyses using finite element analysis software ANSYS Workbench were carried out in order to grasp the maximum Von Mises stresses under iterated tensile loading of the tensile fatigue tests. Fig. 8 shows the image of finite element mesh for sample meshed plate specimen models and Table 2 shows the finite element mesh information for all types of meshed plate specimen models. Material properties of Gum Metal shown in Fig. 2 are used for analytical approach.

From the obtained stress contour plots of sample 90° and 60° axisymmetric specimens also shown in Fig. 8, it can be confirmed that the stress concentrations occurred at the same locations and didn't change so much for different specimen types under different tensile loading. Maximum Von Mises stresses with respect to tensile loads obtained from these analytical results are shown in Fig. 9 of sample meshed plate specimen models with different design variables.

Table 2 Analytical conditions for each meshed GUM METAL plates (90° and 60° axisymmetric models)

Analytical conditions	90°-①	60°-①	90°-②	60°-②	90°-③	60°-③	90°-④	90°-⑤
Element size [mm]	0.124	0.125	0.122	0.125	0.128	0.122	0.129	0.129
Number of elements	179,235	187,380	202,740	187,380	188,995	194,304	163,476	201,246
Number of nodes	232,962	240,695	249,774	240,695	245,046	247,303	201,306	252,679

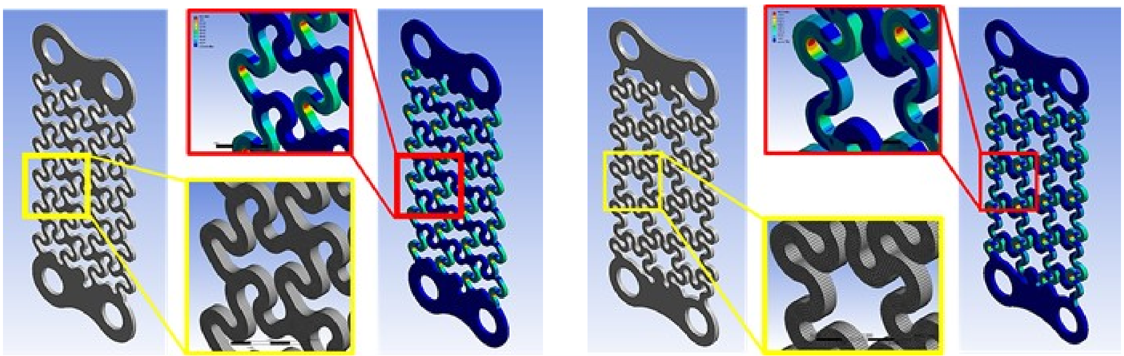

Fig. 8 Finite element mesh and tensile stress results of sample meshed plate models (left: 90°-①, right: 60°-③)

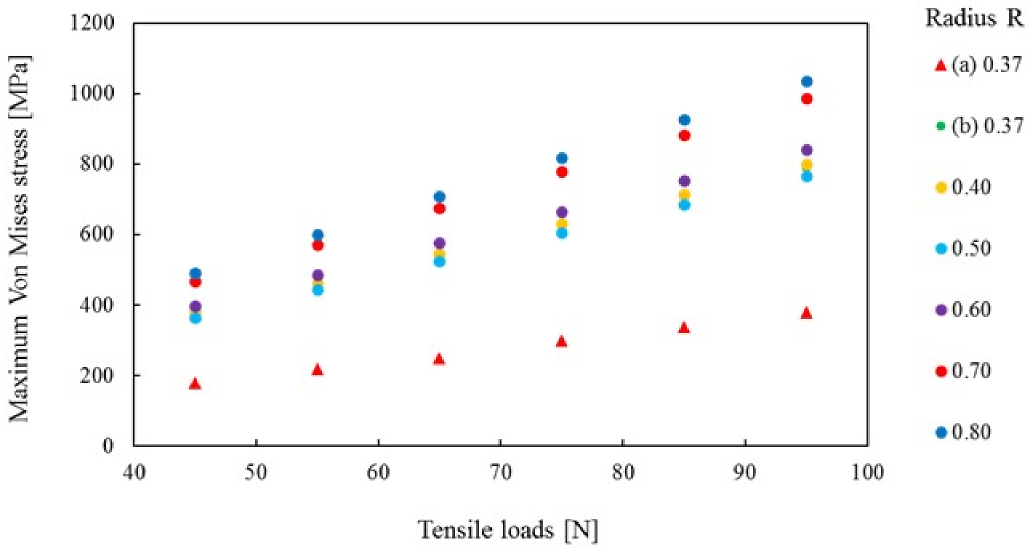

Fig. 9 Maximum Von Mises stress results with respect to tensile loading (90°: circle, 60°: triangle)

Results and Discussion

Tenisle fatigue characteristics of sample meshed Gum Metal plate specimens

Firstly, Fig. 10 and Fig. 11 show the fractured photographs of sample 90° and 60° axisymmetric meshed Gum Metal plate specimens after tensile fatigue tests. Compared with the stress contour diagram of the tensile stress analysis results as shown in Fig. 8, it can be seen that meshed plate specimens fractured at the same location with the stress concentration occurred.

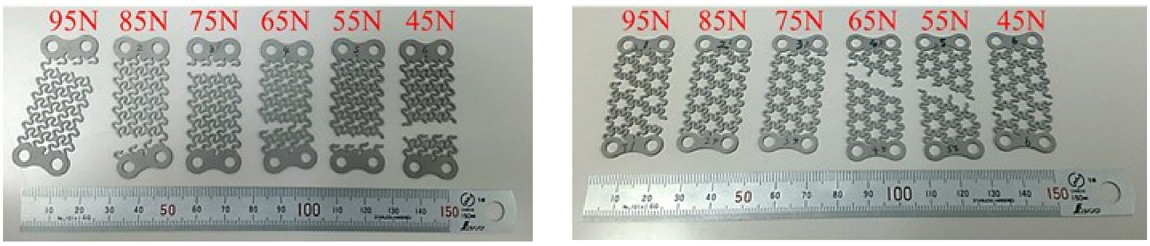

Fig. 10 Meshed Gum Metal plate specimens after tensile fatigue tests
(left: 90° axisymmetric specimen ①, right: 60° axisymmetric specimen ③)

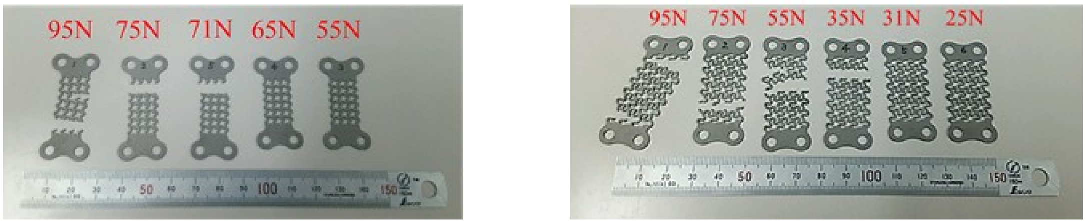

Fig. 11 Improved meshed Gum Metal plate specimens after tensile fatigue tests (left: 90°-④, right: 90°-⑤)

Secondly, the maximum Von Mises stress results are shown in Fig. 12 with respect to maximum iteration number of tensile loading until specimen fractured, combined with experimental and analytical results on the tensile fatigue tests of sample meshed Gum Metal plate specimens. Vertical axis represents the maximum Von Mises stresses under different tensile loads from finite element analysis, and horizontal axis represents the maximum iteration number of tensile loads obtained from the tensile fatigue experiments.

From these results shown in Fig. 12, durability of meshed Gum Metal plate specimens changed little with 60° axisymmetric type specimens under different design variables, which was different with the type of 90° axisymmetric specimens.

On the other hand, the maximum Von Mises stress results of improved meshed Gum Metal plate specimen 90°-④ and 90°-⑤ are also plotted on Fig.12 with respect to maximum iteration number of tensile loading until specimen fractured. From these results shown in Fig. 11 and 12, it can be seen that the improved 90° axisymmetric specimen ④ and ⑤ have both reached the fatigue limit at 10^7 iteration number with lower maximum Von Mises stress value and without specimen fractured. Both improved meshed Gum Metal plate specimens 90°-④ and 90°-⑤ show the same maximum Von Mises stress value approximately 200MPa as the tensile fatigue limit of meshed Gum Metal plates, although under different amplitude of tensile loads.

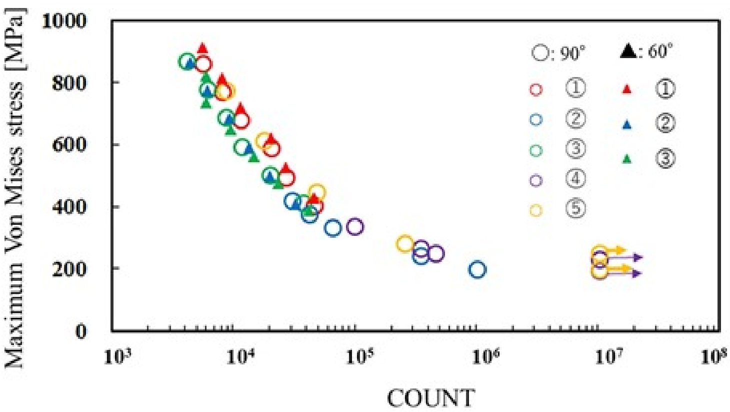

Fig. 12 Combined results of tensile fatigue tests for all sample meshed Gum Metal plate specimens (90°: circle, 60°: triangle)

Improved basic mesh shapes for 90° axisymmetric meshed plate specimens ④ and ⑤ have the following characteristics compared with original 90° and 60° axisymmetric specimens.

(1) Gentle curvatures of S curves caused by the basic mesh shapes
(2) Small S curves with minimum value of radius R of basic mesh shapes
(3) Smaller projected area per basic mesh shape with enough strength to withstand fatigue tensile loads

As the curvature degree of S curve decreases in the improved basic mesh shapes ④ and ⑤, the tensile loads are dispersed and caused lower maximum Von Mises stresses on meshed plate models. It was found that maximum Von Mises stress of the obtained meshed plate specimens can be suppressed and then it's effective to increase the iteration number of fatigue tensile test. It can be concluded that changing the S curves caused by design parameters like radius *R* in basic mesh shapes will affect the stress concentration, and as the results, greatly affect the tensile fatigue characteristics of meshed plate models.

Totally, from the experimental and analytical results obtained in this study, tensile fatigue characteristics of meshed Gum Metal plates are influenced by the stress concentrations mainly caused by S curves of basic mesh shapes. It is considered that for each type of meshed plate specimens, different tensile loads should be determined from finite element analysis to obtain lower than 200MPa maximum Von Mises stresses for meshed Gum Metal plates to reach the tensile fatigue limit at 10^7 iterations.

Conclusion

Experimental and analytical evaluation on tensile fatigue characteristics of meshed Gum Metal plates were executed. From the experimental and analytical results,

(1) Fractures were occurred at the inflectional locations with large curvatures for both type of the specimens, and coincident with the stress concentration locations obtained from analytical results.
(2) The change in curvatures of basic mesh shapes was found to greatly affect maximum tensile stress results. It was also found to effect on experimental results of sample meshed plate specimens, such as the number of cycles at final fractures under different tensile fatigue loads. On the other hand, it was found that changing the central circle diameter D of basic mesh shape would hardly affect the tensile fatigue characteristics of sample meshed plate specimens.
(3) By broadening the tensile load ranges of tensile fatigue tests for different sample specimens, it was confirmed that maximum Von Mises stresses from the sample meshed plate models with different basic mesh shapes can be grasped analytically and then to reach the tensile fatigue limits of meshed plate specimens.

Therefore, design change on meshed structures such as adjustment of the curvature of S curves caused by the pattern of basic mesh shape are effective for improving the fatigue resistance characteristics of meshed plates under tensile loading.

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