Engineering, 2013, 5, 292-296
http://dx.doi.org/10.4236/eng.2013.510B060 Published Online October 2013 (http://www.scirp.org/journal/eng)

Fatigue Life Analysis of Fixed Structure of Posterior Thoracolumbar Pedicle Screw

Tong Yang, Kai Chen, Yonggui Lv
School of Mechanical Engineering, Hangzhou Dianzi University, Hangzhou, China
Email: kchen@hdu.edu.cn

Received July 2013

ABSTRACT

In order to analyze the fatigue life of the posterior thoracolumbar fixed structure, a loading model was established in accordance with the anti-fatigue test requirements specified by ASTM Standard F1717-04. Two three-dimensional Models of the fixed structure with two bars and four bars were built by 3D software (UG), and imported into ANSYS software for static analysis. The maximum and minimum stresses of risk nodes under different loads and moments were obtained. The fatigue life was then calculated using relevant mathematical formula of S-N curve and Goodman curve. It was found that the stress at the middle of the crossbeam between the two bars is larger than the surroundings and is liable to suffer from fatigue.

Keywords: Pedicle Screw; Stress; Fatigue Life

1. Introduction

Instrumented spinal fusion constructs are designed to provide intermediate stability until biological fusion is accomplished. The natural rate of bone healing and remodeling exposes the metallic construct to duty cycles for up to 12 months postoperative period [1]. Pedicle screw technique was first used in spondylolisthesis, and quickly spread to trauma, degeneration, deformity correction and reconstruction after resection of the tumor treatment, and many other disease treatments [2]. Although many studies have been done focusing on the biomechanical aspects of pedicle screws [3,4], few research has been seen working on the fatigue life of the thoracolumbar fixed structure. Recently, titanium and its alloys have gradually replaced stainless steel as preferred biomaterials for lumbar spinal applications because of their radiographic safety and better physical performance [5,6]. This paper analyzed the fatigue of the fixed structure of thoracolumbar pedicle screw using FEM method.

2. Fixed Structure and Static Model

2.1. Thoracolumbar Fixed Structure

The titanium alloy TC4 plate was chosen for calculation. TC4 plate has such features as lightness, high strength, good fatigue performance. It is also corrosion resistant in chloride, hydroxide and sulfide environment. The material properties of titanium alloy TC4 are: 1.13×10^5 MPa of Elastic Modulus, 0.3 of Poisson Ratio, 875 MPa of Yield Stress, 925 MPa of Yield Limit. In this paper, the fixed structure of the pedicle screw shown in **Figure 1** consists of two beams that are connected with a perpendicular bar, and with screws at the ends. The diameter of the beam is 6 mm and its length is 105 mm. It is usually used in the treatment of the two or three thoracolumbar fixation surgery. If needed, the length of the structure can be extended to less than 410 mm through fixed connections for wider applications.

2.2. Static Model

Thoracolumbar fixed structure is punctured into human spine through pedicle screws. The force is transmitted through the fixed structure to protect the broken spine. Some researches demonstrated that the fusion rate of the patients is higher if the spinal internal fixation is used [7,8]. In order to mesh and calculate conveniently, the pedicle screws and their host structure are characterized as an integral part in this model. The simplified three-dimensional model is shown in **Figure 2**.

The normal fatigue test for the thoracolumbar fixed structure is as follows: the thoracolumbar fixed structure is first screwed into the prepared plate fixation module made of UHMWPE (ultra high molecular weight polyethylene module), shown in **Figure 3**. A pair of metal bar inserted into the UHMWPE module connects the test block with the chuck of the fixing apparatus on the material testing machine. The UHMWPE module and the thoracolumbar fixed structure need to be replaced for

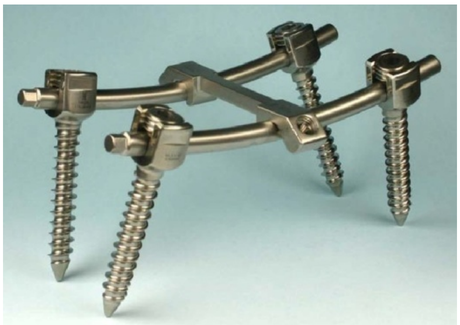

Figure 1. A typical thoracolumbar fixed structure.

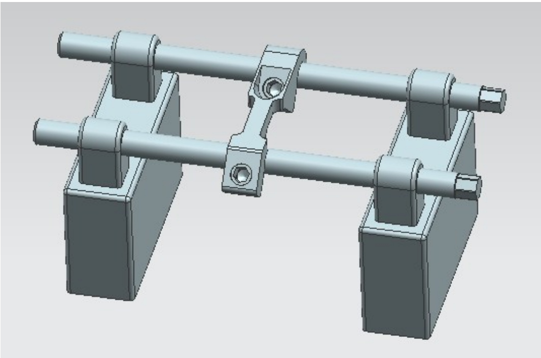

Figure 2. Simplified 3-D model with beam and bar structure.

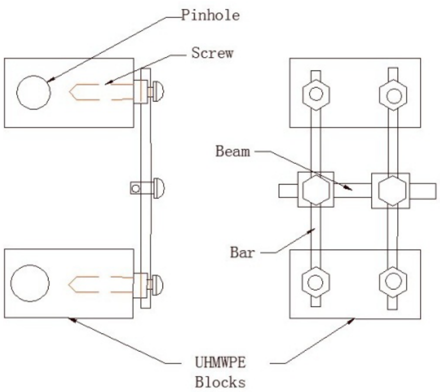

Figure 3. Fatigue test apparatus for thoracolumbar fixed structure.

each fatigue test.

According to the above described prototype of the fatigue test and the actual behavior of human vertebral body bending and lateral bending movement, a compressive load, a tensile load, a bending moment and a lateral load were added respectively for FEM analyses, as shown in **Figure 4**. Compressive loads and tensile loads of 100 N, 140 N, 180 N, 200 N and 220 N were used for the first run of calculation, bending moments of 200 Nmm, 300 Nmm, 400 Nmm and 500 Nmm were used for the second run of calculation, and lateral loads of 20 N, 40 N, 60 N and 80 N, were used for the third run of calculation.

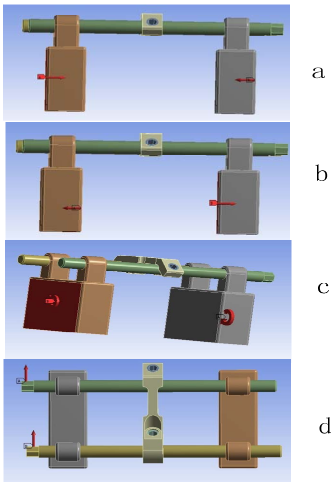

Figure 4. Four loading methods: (a) Compressive load; (b) Tensile load; (c) Bending moment; (d) Lateral load.

3. FEA and Fatigue Calculation

The finite element analysis (FEA) by ANSYS software was carried out for the type of thoracolumbar fixed structure with four corresponding loads. The fatigue lives of each load type were then calculated and listed in tables for comparison.

3.1. The Finite Element Mesh Model

The simplified three-dimensional model was created using the 3-D solid-building software UG (Version 6.0). Then the 3-D model was imported into Workbench statics analysis module of ANSYS. The whole-size control method was used for grid partition. The mesh unit solid185 is a small, six-degree freedom tetrahedron. The two beams and one bar were controlled with 1 mm unit size and the rest was controlled with 1.2 mm unit size. Automatic grid partition with same solid185 unit was applied on two UHMWPE holding blocks, screws, bar and beams. The meshing result was shown in **Figure 5**.

3.2. FEA Results

Four different loading methods were applied for cal- culation after grid generation: a pair of compressive loads, a pair of tensile loads, a pair of bending moments and a single lateral load were added on UHMWPE holding blocks respectively, as shown in **Figure 3**. Some results of the calculated stress clouds for the four loading types were shown in **Figures 6-9**.

From **Figures 6**, **7** and **9**, it can be seen that higher stress is distributed in the connection area of the beam and bar when the structure is loaded with compressive force, tensile force and lateral force. When the structure is loaded with bending moment, higher stress locates in the area of the middle of the beam, as shown in **Figure 8**.

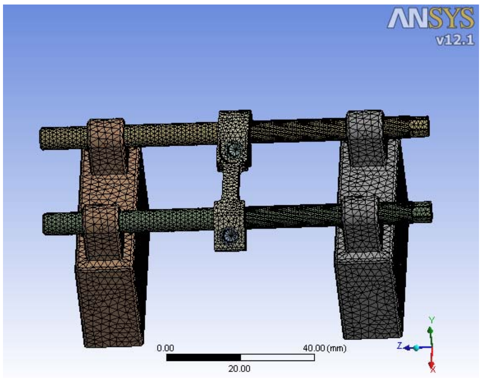

Figure 5. Mesh model.

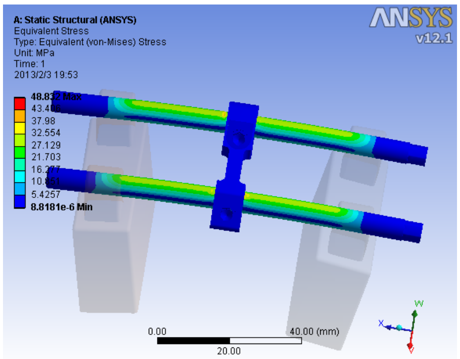

Figure 6. Stress cloud for compressive load of 50 N.

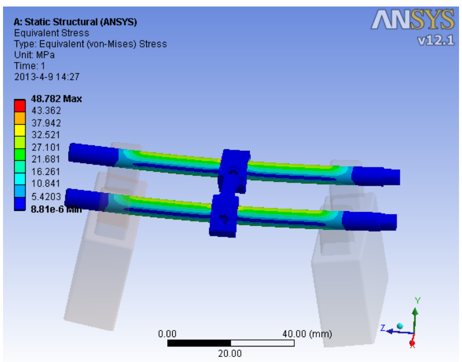

Figure 7. Stress cloud for tensile load of 50 N.

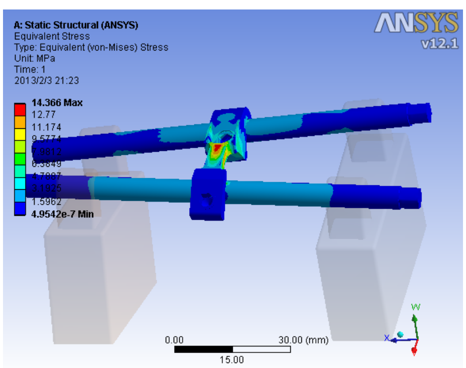

Figure 8. Stress cloud for bending movement of 150 Nmm.

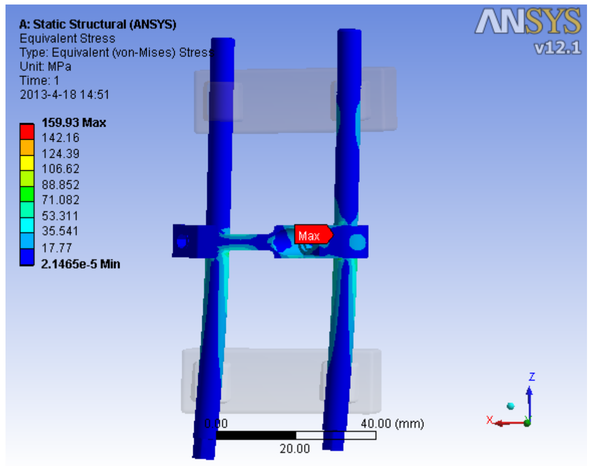

Figure 9. Stress cloud for lateral load of 60 N.

Table 1 lists the maximum stress of different compressive and tensile loads. It can be seen that the maximum stress is approximately the same for same loads of compressive and tensile methods, and approximately increases linearly with the loading force.

3.3. Calculation of Fatigue Life

The classic stress fatigue theory relates the stress (*S*) with the fatigue life (*N*) by the S-N curve formula:

$$S^m N = C \tag{1}$$

where *m* and *C* are the parameters associated with material properties, stress ratio, and the corresponding loading method.

m can be calculated by taking two points of the high cycle fatigue *S*-*N* curve for TC4 [9], as shown in **Figure 10**, using the following formula:

$$m = \frac{\log_{10}\left(N1/N2\right)}{\log_{10}\left(S2/S1\right)} \tag{2}$$

and C is calculated with:

$$C = N1 * S1^m \tag{3}$$

where (*N*1, *S*1) and (*N*2, *S*2) are any of two points on the *S*-*N* curve.

Goodman Curve follows the following relationship:

$$\frac{S_a}{S_{-1}} + \frac{S_m}{S_u} = 1 \tag{4}$$

where S_a is the average stress, S_m is stress amplitude, S_{-1} is stress cycling characteristics of the stress at cycle for symmetry, S_u for material fatigue limit.

Combining the *S*-*N* curve and Goodman curve, the circle life *N* the cervical steel plate can be calculated by the following steps:

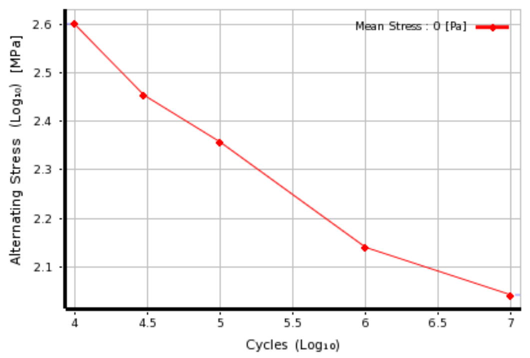

Figure 10. High cycle fatigue *S-N* curve for TC4.

Table 1. Different compressive and tensile loads and their highest stress.

Load	Max Stress (MPa)	
	Compressive	Tensile
50 N	48.4	48.9
100 N	97.6	97.7
140 N	136.7	136.6
200 N	195.3	195.4

$$S_u = 0.6 \times S_s \quad (5)$$

$$S_a = \frac{(S_{\max} - S_{\min})}{2} \quad (6)$$

$$S_m = \frac{(S_{\max} + S_{\min})}{2} \quad (7)$$

$$S\_a = \frac{S_a}{(1 - S_m / S_u)} \quad (8)$$

$$N = \frac{C}{(S\_a)^m} \quad (9)$$

where S_{max} is the maximum work stress of the plate under loads, S_{min} the minimum work stress under load, S_s the tensile strength for TC4, S_a the cyclic stress corresponding to the stress ratio $R = -1$.

The fatigue circle life N was calculated for the type of the thoracolumbar fixed structure under four loading methods. The results were listed in **Table 2**.

From **Table 2** it can be seen that the maximum stress increases with the increasing load, while the fatigue life decreases. US standard ASTM F1717-13 [1] requires a fatigue life of 5 million times without any damage, while China's domestic requirement is 1 million times without any damage. Under the compressive load of 200N, or the bending moment 500N, or the lateral load of 60N, the fixed structure has fatigue life larger or close to 5 million times. When the body side bends, its lateral load is small. As the load increases, the fatigue life number decreases dramatically. When the compressive load is lager than 195.3 N or the lateral load is lager than 80 N, the fatigue life is less than 5 million but greater than China's domestic requirement.

Table 2. The fatigue life of thoracolumbar fixed structure.

Compressive load (N)	Max stress(MPa)	Fatigue circle life (10^6)
100	97.6	400
140	136.7	50
180	175.7	14.7
200	195.3	5.0
220	214.3	2.6
Bending moment (N.mm)	Max stress (MPa)	Fatigue circle life (10^6)
200	19.2	4.18×10^6
300	28.7	4.53×10^5
400	38.3	9.02×10^4
500	47.9	2.55×10^4
Lateral load (N)	Max stress (MPa)	Fatigue circle life (10^6)
20	53.311	1.39×10^4
40	106.62	237
60	159.93	18.7
80	213.25	2.72

4. Conclusion

The FEM analyses of thoracolumbar fixed structure were carried out in this study. The stress distribution of the fixed structure was studied under four different types of loads: compressive loads, tensile loads, bending moment loads and lateral loads. The FEM results show that the most fragile part under bending moment is the central part of beam. When the fixed structure was loaded with compressive load, tensile load and lateral load separately, the most fragile part is the connection area between beam and bar. The fatigue life numbers were calculated through S-N curve and Goodman curve after FEM analyses under different types and different values of loads. The calculation results show that the fatigue life decreases rapidly as the value of the load increases. The type of thoracolumbar fixed structure meets the China's domestic requirement of 1 million time under the compressive or tensile loads of 100 - 220 N, bending moment loads of 400 - 500 Nmm or lateral loads of 20 - 80 N.

REFERENCES

[1] ASTM Standard F1717, "Standard Test Methods for Spinal Implant Constructs in a Vertebrectomy Model," ASTM International, West Conshohocken, 2013. http://dx.doi.org/10.1520/F1717-13

[2] P. R. Harrington and H. S. Tullos, "Reduction of Severe Spondylolisthesis in Children," *Southern Medical Journal*, Vol. 62, No. 1, 1969, pp. 1-7.

[3] E. Wagnac, D. Michardière, A. Garo, P. J. Arnoux, J. M. Mac-Thiong and C. E. Aubin, "Biomechanical Analysis of Pedicle Screw Placement: A Feasibility Study," *Studies in Health Technology and Informatics*, Vol. 158, 2009, pp. 167-171.

[4] Y. Wang, A. M. Jin and G. F. Fang, "Three-Demesional Finite Element Analysis of the Lumbar Pedicle Screw Instrumentation," *Journal of Clinical Rehabilitative Tissue Engineering Research*, Vol. 12, No. 48, 2008, pp. 9439-9442.

[5] F. B. Christensen, B. K. Nielsen, E. S. Hansen, S. Pilgaard and C. E. Bunger, "Anterior Lumbar Intercorporal Spondylodesis. Radiological and Functional Therapeutic Results," *Ugeskrift for Laeger*, Vol. 156, No. 37, 1994, pp. 5285-5289.

[6] K. B. Sagomonyants, M. L. Jarman-Smith, J. N. Devine, M. S. Aronow and G. A. Gronowicz, "The *in Vitro* Response of Human Osteoblasts to Polyetheretherketone (PEEK) Substrates Compared to Commercially Pure Titanium," *Biomaterials*, Vol. 29, No. 11, 2008, pp. 1563-1572. http://dx.doi.org/10.1016/j.biomaterials.2007.12.001

[7] L. Mark, Z. Michael, S. Paul, V. Lori, C. M. Ann, B. Raj and C. Richard, "A Comparison of Single-Level Fusions With and Without Hardware," *Spine*, Vol. 16, No. 8, 1991, p. 455.

[8] P. D. Angevine, C. A. Dickman and P. C. McCormick, "Lumbar Fusion with and Without Pedicle Screw Fixation: Comments on a Prospective, Randomized Study," *Spine*, Vol. 32, No. 13, 2007, pp. 1466-1471. http://dx.doi.org/10.1097/BRS.0b013e318060ccca

[9] H. S. Lai, Y. J. Li, F. Z. Xuan and S. D. Tu, "High Cycle Fatigue in Ti-6Al-4V Titanium Alloy," *Journal of Nanjing University of Technology*, Vol. 31, No. 5, 2009, pp. 15-19.

