National Conference with International Participation
ENGINEERING MECHANICS 2003
Svratka, Czech Republic, May 12 – 15, 2003

paper no.
322

MODELLING AND SIMULATION OF MECHANICAL PARAMETERS OF BONE FRACTURE SLOT USING EXTERNAL FIXATION

D. Jasińska-Choromańska[1], **I. Sadzyński**[2]

Summary:*Long bone fractures can be healed using external fixators – devices that stiffly fix fracture fragments using parallel to the bone, attached with pins frame. This method affords to take profits both from healing and diagnostics of fracture during osteogenesis. Osteogenesis can be precisely determined with mechanical properties like strenght and stiffness inside the fracture slot. The treatment of long bone fractures by external fixators affords an unique opportunity to control the healing of the fracture by measuring the tension on the frame, that occurs under the load given to the bone and rely on the mechanical properties of the fracture. Young modulus can be one of the best description methods of mechanical properties of the bone. It can also be used for more precise and direct description of changes of mechanical properties inside the fracture slot. The paper presents methods and results of the assessment of mechanical properties changes during fracture healing.*

1. Introduction

External fixation. Frequent injuries, bone fracture, an effect of loads much larger than the bone can carry, can be healed by using external fixators. Fracture fragments should be relatively stiffly fixed together to provide best healing condition (Jasińska-Choromańska et. al.,2000). To fix both parts of the broken bone the external fixator provides stiff frame, parallel to the bone, rigidly attached to the bone with pins (see Fig.1)

This method of fracture healing gives an unique opportunity to benefit from both healing and diagnostics during the osteogenesis (bone growth process).

Clinical and experimental observations have demonstrated that fracture healing process (osteogenesis) changes broken bone condition in a particular physiological way. The phases of bone fracture healing are associated with relative paucity and formation of callus and osteonal remodelling across the fracture line. The non-invasive evaluation of fracture healing may allow more precise timing of fixation device removal, recommendation for progression from non-weight bearing to full weight bearing, and to the prediction of abnormal fracture healing such as delayed union or non-union. The common techniques include manual

[1,2] ,Warsaw University of Technology, Faculty of Mechatronics, Institute of Micromechanics and Photonics, A.Boboli 8 Str., 02-525 Warsaw, Poland
[1] DSc Danuta Jasińska-Choromańska, email: danuta@mchtr.pw.edu.pl
[2] MSc Igor Sadzyński, e-mail: isadzynski@comesa.pl

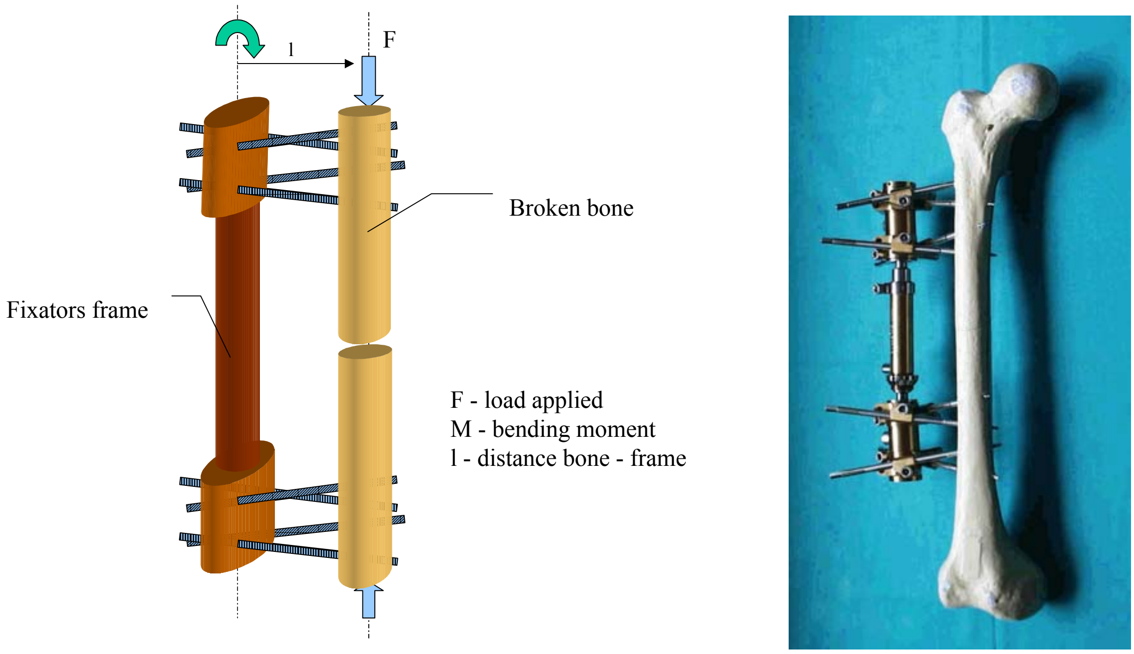


Fig. 1. Diagram of external fixator showing major components and applied loading with photo

examination of the fracture for stability, radiographic evidence of healing, and the empirical passage of time. Traditional diagnostics methods: X-ray techniques such as radiography, radiographic densitometry, Computed Tomography provide the information concerned to mineral properties of the healed fracture and fracture site, and can describe the fracture healing as a process of calcification. This may not be sufficient to evaluate the real fracture condition and cause a risk of non-union or refracture. Many fractures can bear load before their “empirical healing time” and are therefore immobilised for an unnecessarily long period. Others are freed too soon and may sustain refracture or develop malunion after early activity. A fracture that is sufficiently healed to allow normal activities may not have sufficient strength for strenuous work or vigorous sport.

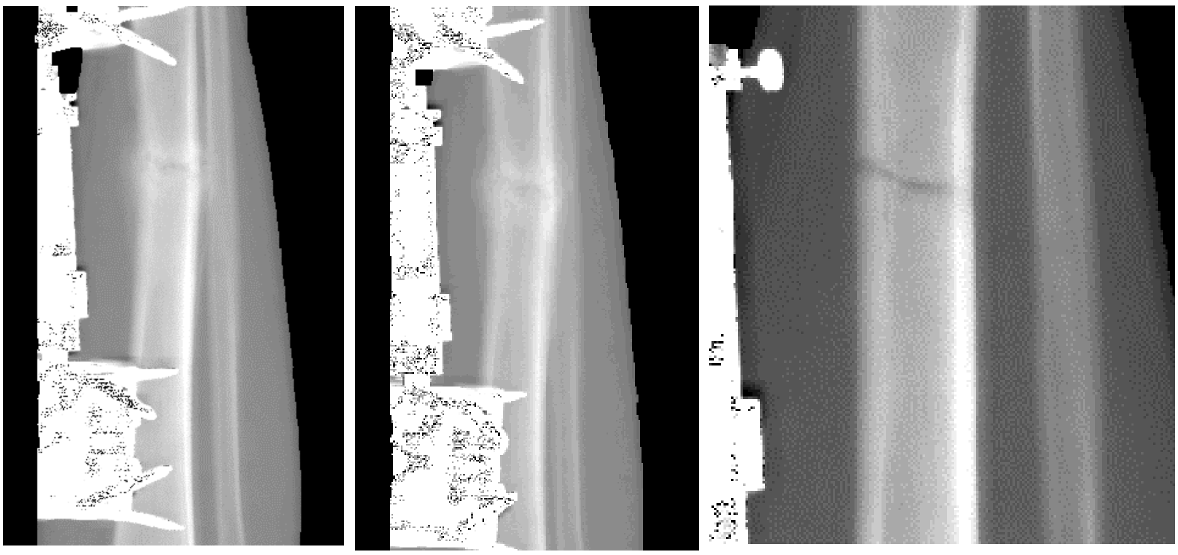
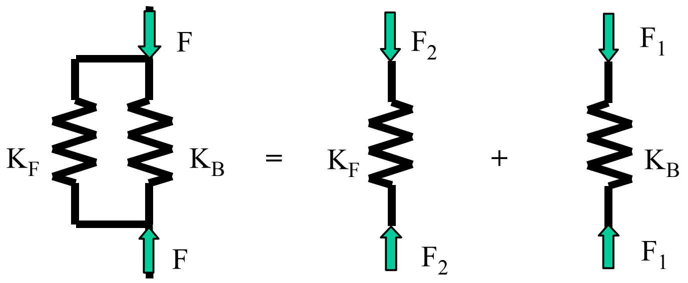


Fig.2 The healing of fracture as a process of calcification: 2, 122 and 137 days after injury

Fracture mechanics The treatment of the fracture using external fixators enables diagnosis of the healing process by measuring the mechanical properties inside the fracture slot. Direct measurement of mechanical properties of the healed bone treated by external fixators gives precise information about the fracture conditions. The measurement of the strain in the fixator frame by strain gauges was developed by Burny et al. (1978) and was subsequently improved in the next years (Cunningham,1994). The method provides an opportunity to find a bone-healing pattern based on mechanical properties of the fracture and to propose a measure of healing of fracture, which would define the stadium of the healing process.

Idealised model of bone-fixator system (Fig. 2) consists of a load F_1 carried by healed bone and load F_2 carried by fixator's frame , which give the total load applied to the system F:



$$F=F_2+F_1 \quad (1.1)$$

Fig. 3. Diagram of idealised fixator system as two spring system

The fracture stiffness consists in the large majority of the compression stiffness when the frame stiffness is divided between the compresion and bending stiffness, what was later assumed as a total frame stiffness (Jasińska-Choromańska et.al.,2000).

Bone structure Compliceted structure of the bone like other tissues can be described as hierarchical. The hierarchy levels: bone shape, type of bone, osteons (bone fibers) and molecules define different mechanical properties and have their influence on the bone mechanical properties. Cortical and trabecular bone tissues have also anisotropic characteristics. The wide range of measurements of mechanical properties of the healthy bone was performed on the main levels of hierarchy and in main directions. The elasticity modulus of the cortical and trabecular bone was assessed using standard mechanical testing techniques and ultrasonic measurements. The differences in stiffness between different types of bones and mineralization levels were found and assesed (Currey 1998, Schaffler and Burr 1988). Ascenzi et al. performed also measurement of the mechanical properties of the single osteon (Ascenzi et.al., 1994). The table presents examples of the results of elasticity modulus of the bone as a one of the mechanical properties of the bone:

Bone type	Mechanical Test	Elasticity Modulus
Cortical bone	Transverse elasticity	15-20 GPa
	Longitudinal Elasticity	8-10 GPa
	Longitudinal Compression	6 GPa
	Transverse Compression	9 GPa
Cancellous Bone	Tensile testing	2 GPa

2. Materials and methods

The use of external fixators enables the assesment of mechanical properties of the healed bone inside the fracture slot during each phase of healing. The clinical measurements of the changes of fracture slot stiffness was performed using Dynastab fixator and characteristics of changes of bone strength in time were obtained.

Fig.4.Patient during clinical examination

Laboratory simulations of changes of mechanical properties inside the fracture slot were performed using Dynastab fixator and testing machine. To simulate the healing process and to obtain progressive strength characteristics 16 different kinds of materials with different mechanical properties were put into the fracture slot. The total load, the longitudinal compression forces on the frame, and the interfragmentary movements were measured (Jasińska-Choromańska, Sadzyński, 2001). The comparison of datas obtained in clinical measurements and in laboratory simulation allows to assign each material into particular phase of fracture healing (fig. 5).
To assess mechanical properties of the materials used for simulation of fracture site elasticity modulus of each material was measured using Instron material testing equipment. The strain/stress characteristics of each material under the compression load were obtained and the Young's modullus was calculated. The elasticity modulus of each material can be therefore assign into particular phase of fracture healing, and the characteristics of the changes of Young's modulus during the time of fracture healing can be obtained. According to the model of idealised fixator system presented on fig. 2 the total load is divided between the load carried by the frame and the load carried by the bone. The stress on the bone-fixator system is therefore the sum of the stress on the frame and on the bone, and the total elasticity modulus is the sum of elasticity modulus of the frame and the elasticity modulus of the bone.The tests showed that the elasticity modulus of the frame depends strictly on the fixator's geometry

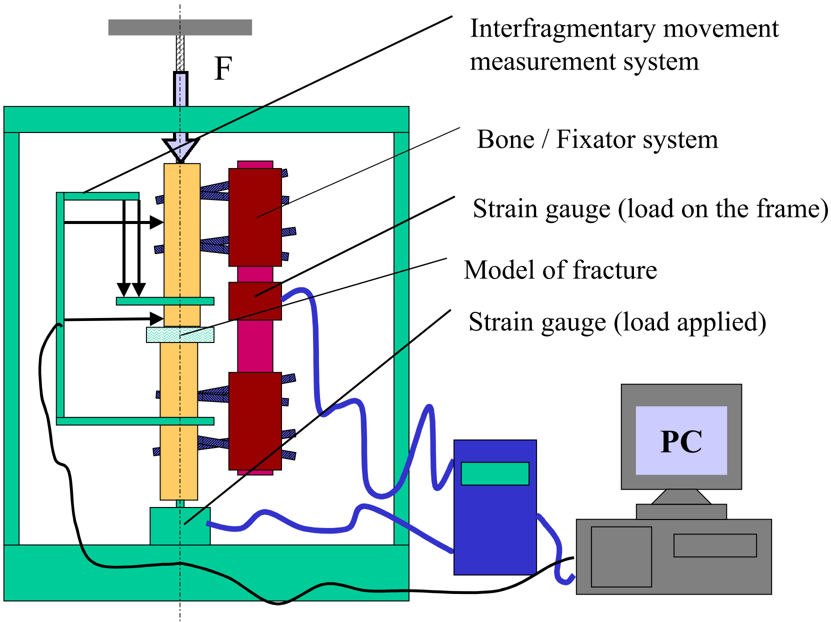


Fig. 4. Testing Machine - schematic

where the total stiffness was considered as the sum of the compression and bending stiffness as it was demonstrated below. The geometry of the bone-fixator system during all tests were kept unchanged and therefore the elasticity modulus of the system remained on the same value of 4 MPa. From the laboratory tests' results the Young's modulus of the fracture slot can be computed. To verify these resuls the measurement on simulation materials were performed. The assessment of Young modulus is presented on the graps on fig. 6.

The elasticity modulus at the end of the healing process are different from the Young's modulus of the healthy bone. The clinical decisions about removals of fixators were made on the basis of RTG diagnosis. The device removal were therefore done before the bone reached the last stage of healing process, however the strength of the bone was sufficient to the weigth bearing.

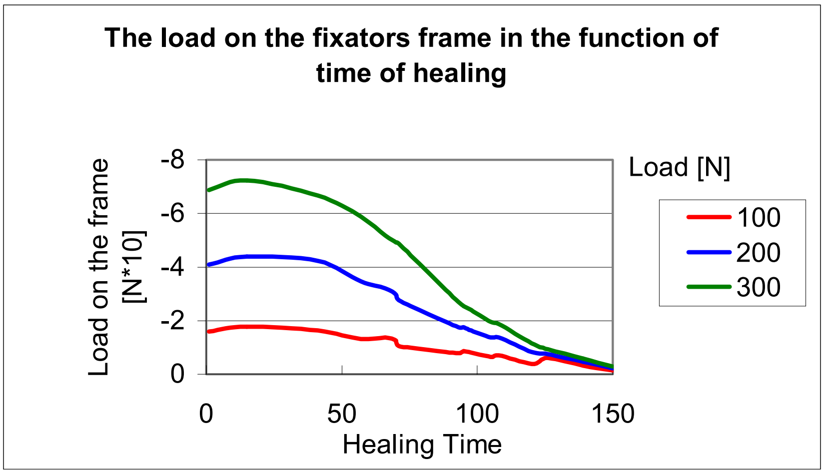


Fig.5. The results of fracture simulation in comparison with clinical examination

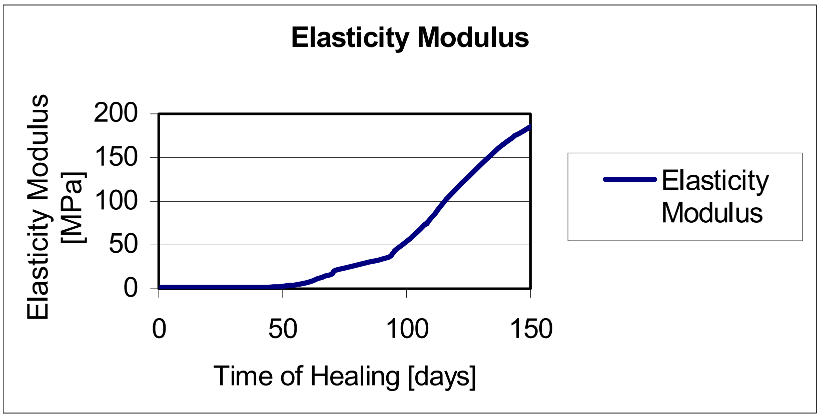


Fig. 6 The changes of Young's modulus during the time of fracture healing

3. Discussion

The noninvasive evaluation of fracture healing may allow more precise timing of fixation device removal, quantitative recommendations for weight bearing, and the prediction of abnormal fracture healing patterns.

The measurement of mechanical properties of the fracture slot could provide an objective quantitative measure of fracture healing. Direct measuring of longitudinal compression on the fixator frame can more precisely describe the fracture condition. The Young's modulus of the fracture slot can be computed from the results of measurement of the load on the fixator's frame, according to particular bone-fixator system geometry. This provides means to assess fracture healing (measure of fracture healing) and fracture healing pattern in mechanical terms independent of the type of the bone and bending moment originated from the distance between the frame and the bone. The measure of fracture healing as a result of measuring of longitudinal compression, can also be applied in clinical practice as one of the method of fracture condition assessment. The model of the mechanical properties of the fractured bone during healing and the simulation of healing processes applied to computer techniques can give the information about phase of healing in the diagnostics that uses external fixation.

4. References:

Ascenzi A., Bonucci E.: The tensile properties of single osteons, *Anat. Rec.*, No. 158, pp. 375-86

Chehade M.J., Nawana N., Pearcy M.J., Pohl A.P.: Clinical implications of stiffness and strength changes in fracture healing. *J Bone Joint Surg. [Br]* 1997; 79-B: 9-12

Cunningham J.L., Goodship A.E., Kenwright J., O'Connor B.T., Richardson J.B.: Measuring stiffness can define healing of tibial fractures. *J Bone Joint Surg. [Br]* 1994; 76-B: 389-394.

Goodship A.E., Kenwright J., Rigby H.S., Watkins P.E.: The role of fixator frame stiffness in the control of fracture healing. An experimental study. *J. Biomech.* 1993; 1027-1035.

Jasińska-Choromańska D., Choromański W.: Mechatronic orthopaedic fixators – theory computer design and clinical practice *Proceedings of 12th Conference of The European Society of Biomechanics Dublin 2000* p.423.

Jasińska-Choromańska D., Deszczyński J., Karpiński J.: Computer analysis of the influence of three- dimensional layout of bone implants on stability of fracture fixation. *Ortopedia, Traumatologia, Rehabilitacja* No 1, 14/1999, pp. 35-38, in polish.

Jasińska-Choromańska D., Sadzyński I.: Monitoring techniques of bone fracture healing using external Fixation, *Proceedings of the Conference: Experimental Stress Analysis, Tabor 2001.*

Jasińska-Choromańska D., Sadzyński I.: Movements of bone fragments in fractures healed using external fixation. *Acta of Bioengineering and Biomechanics: Proceedings of the International Conference Biomechanics 2001*, Zakopane 3–6.09.2001, in polish

Jasińska-Choromańska D.: Modelling and computer simulations in design of unilateral orthopaedic external fixators. Oficyna Wydawnicza PW 2001, z. 186, in polish.

Young Rho J., Ashman R.B., Turner C.H.: Young's modulus of trabecular and cortical bone material: ultrasonic and microtensile measurement. *J. Biomech.* Vol. 26, No. 2, 1993, pp 111-119.