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Experimental and numerical approach to chosen types of mandibular fractures cured by means of miniplate osteosynthesis

MAGDALENA KROMKA*, GRZEGORZ MILEWSKI

Institute of Applied Mechanics, Cracow University of Technology,
Al. Jana Pawła II 37, 31-864 Kraków, Poland

The paper presents experimental and numerical analyses of two cases of mandibular corpus fractures cured by means of miniplate implantation. In the laboratory tests, strain gauges and electronic speckle pattern interferometry methods were used, while in the numerical simulations finite element analyses were applied. The aim of such a combined approach was to verify a correctness of the numerical model applied with regard to the assumptions and simplifications which had been done when creating FEM for human mandible: healthy, broken and stabilized with miniplate implants.

Key words: *strain gauges, ESPI, FEM, mandibular fractures*

1. Introduction

Numerical modelling by means of finite element method (FEM) renders possible analysis and assessment of certain mechanical states in bone structures in order to estimate various problems appearing during medical treatment. However, numerical simulations, in general, need some simplifications with regard to real biological structures, in this case with regard to the anatomy of human stomatognathic system. The correctness of the assumptions and simplifications applied has to be verified experimentally. Two independent experimental methods were used: strain gauge method and electronic speckle pattern interferometry (ESPI)[1]. Two kinds of the most often cases of mandibular corpus fractures were considered: one-side and mutual fractures [1].

2. Aim of the paper

The aim of the experiments carried out was to describe the strain states in chosen areas of mandibular bones of healthy and broken mandibles and then to compare the results obtained with relevant analyses by means of FEM.

3. Material and methods

The strain gauge experiments were done using a mandibular model made of epoxy resin, a scale of 1:1, while in the electronic speckle pattern interferometry the experiments were carried out on anatomical preparation of human mandible taken *post mortem*,

* Corresponding author: Institute of Applied Mechanics, Cracow University of Technology, Al. Jana Pawła II 37, 31-864 Kraków, Poland. E-mail: mkromka@mech.pk.edu.pl

[1] The experiments were carried out in cooperation with the Division of the Institute of Biomedical Engineering and Experimental Mechanics, Wrocław University of Technology.

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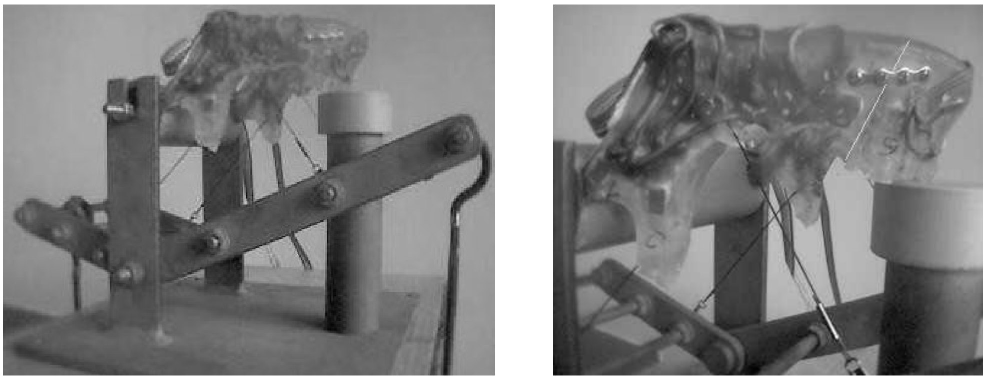

Fig. 1. Experimental stand for strain gauge tests

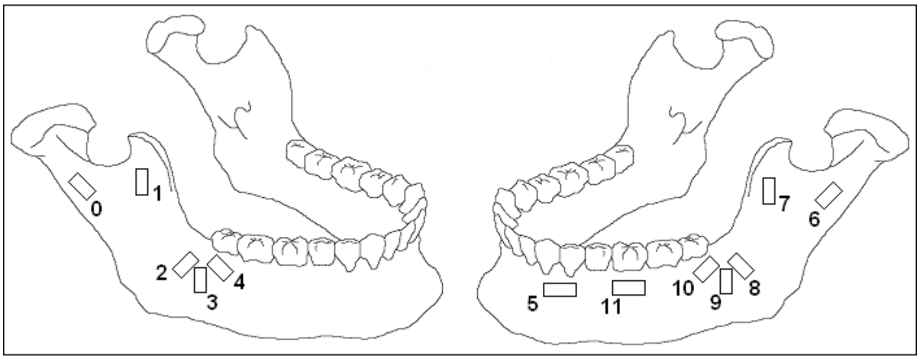

Fig. 2. Strain gauge arrangement on epoxy model of mandible

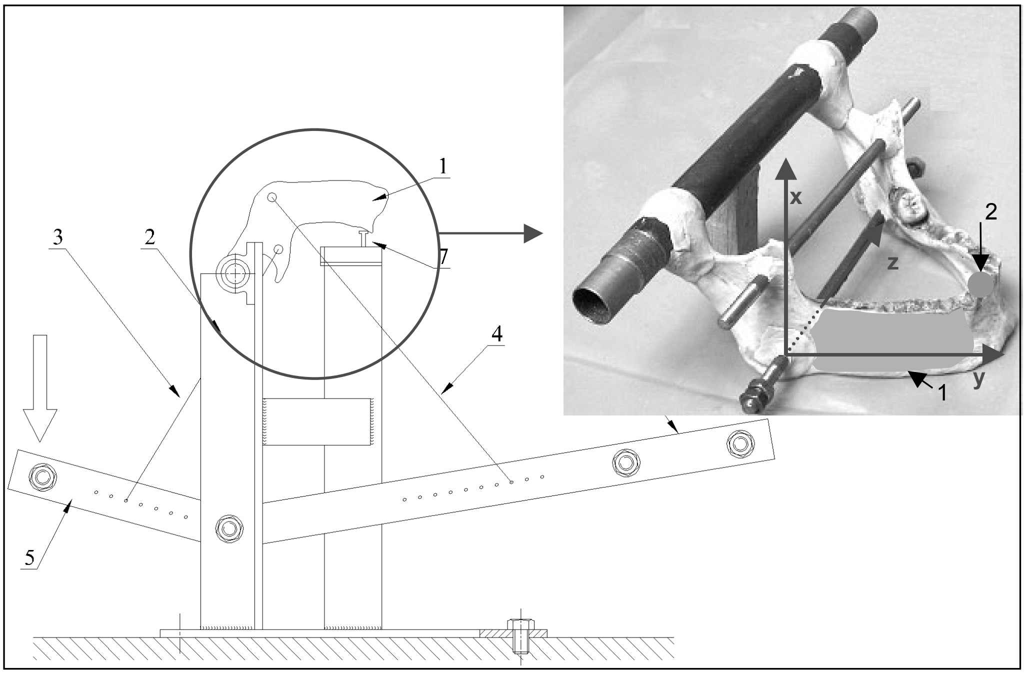

Fig. 3. Setup for investigating mandibular bone displacements:
1 – mandible, 2 – frame, 3, 4 – ties, 5 – loading lever. Anatomical preparation of human mandible with modelled: 1 – displacement constrains, 2 – mobility of temporal-mandibular joint, 3, 4 – areas of activity of masseters and temporal muscles

two weeks after death. Both epoxy model and anatomical preparation were examined on similar experimental stands where occlusal loadings corresponding to physiological bite activity were transferred by mandibular muscles (figures 1 and 3). In strain gauge tests, two groups of muscles were considered, i.e., masseters and temporal muscles, while in ESPI experiment, medial pterygoid muscle was additionally examined [2], [3]. Mobility of temporal–mandibular joint in both cases was modelled by one-degree of freedom corresponding to in-plane pivot.

Twelve strain gauges were cemented to both buccal sides of mandibular ramus and corpus: two rosettes and six separate sensors (figure 2).

A human mandible used in ESPI method was anatomically prepared in a special way. All soft tissues with periosteum and teeth were removed and then the external surfaces of the mandible were painted in order to get a uniform measurement background (figure 3).

Numerical models of mandible (healthy, broken and stabilized with miniplates) were constructed based on the CAD FEMAP® and FEM ANSYS® programs. The details of the numerical procedures were discussed and presented in our previous papers [4]. Figure 4 shows the FEM models for two cases of miniplate fixations of broken mandibular corpus described in the paper.

Strain gauge experiments were carried out for healthy mandible and broken mandibular body in area close to the 33rd and the 34th teeth (i.e., between left canine and premolar) stabilized with Co–Cr–Mo stainless steel plate from the Martin system [5]. For each case a series of 15 measurements were recorded for the following values of occlusal loadings: 25 N for masseters and 5 N for temporal muscles. The values of forces corresponded to the occlusal loads characteristic of the first stage of mandibular fractures when a patient undergoes fluid intake.

In order to compare the strain gauge recordings and numerical FEM calculations, the same simplifications as those taken into account in physical experiment should be made for the numerical model. The volume of callus in the area of fracture was removed from the original model of mandible. The activity of a medial pterygoid muscle was neglected, and the parts of temporal muscles were limited to one-side attachments on the coronoidal process of the mandible. In the calculations, all the elastic material properties of compact and trabecular mandibular bones were taken the same as those for epoxy resin, i.e., Young's modulus $E = 3200$ MPa and Poisson's ratio $\nu = 0.3$, and the total occlusion was distributed as follows: 25 N for masseters and 5 N for temporal muscles. The results of FEM analysis for healthy mandible and mandibular fractures for both cases of miniplate fixations are presented in figure 5.

In numerical simulations, the medium values of strain components were calculated from 5–6 neighbouring nodes corresponding to the areas with strain gauges and were compared with the relevant medium values from the series of registered strain values.

ESPI is a non-contact full-field optic system that measures the displacement and strain fields at any surface of a diffuse reflecting object. Thus, on the surface of mandibular corpus of anatomical human preparation a "virtual strain gauge" area of a size of 3×4 mm was chosen corresponding to the size of real strain gauge rosette base (figure 6). The method was discussed in [6]. The mean values of the strain components, i.e., ε_x (vertical axis between mandibular angle and coronoidal process) and ε_y (horizontal axis along mandibular corpus), were calculated for healthy mandible and two kinds of corpus fractures: one-side fracture and mutual fracture and then compared with relevant FEM results.

4. Discussion of the results

The comparison of the results of strain gauge experiments and FEM calculations for one-side corpus fracture is presented in table 1 and figure 7 for separate strain gauges and in table 2 and figure 8 for the rosettes for the principal strain values ε_1 and ε_2.

Based on the set of data it can be concluded that in the case of strain gauge rosettes the results obtained are compatible with numerical calculations. An average error for rosette (2–3–4) was 23%, and for rosette (8–9–10), 13%. For separate gauges the values of an average error for healthy mandible and for broken one reach 20% and 25%, respectively.

For some separate strain gauges the differences are much bigger. Moreover, the asymmetry of mandibular work for left- and right-hand side ramus and condylar neck was noticed. We suppose that those differences appeared due to the imperfections of experimental stand, which enabled only in-plane pivot of temporal-mandibular joint and due to a lack of perfect fixation of ties representing mandibular muscles.

In the ESPI method, the percentage differences between strain values along the X-axis and Y-axis for the cases of healthy mandible and broken one (one-side fracture and mutual mandibular fractures) with regard to FEM simulations are shown in figure 9.

For healthy mandible the compatibility of both experimental and numerical results is almost perfect,

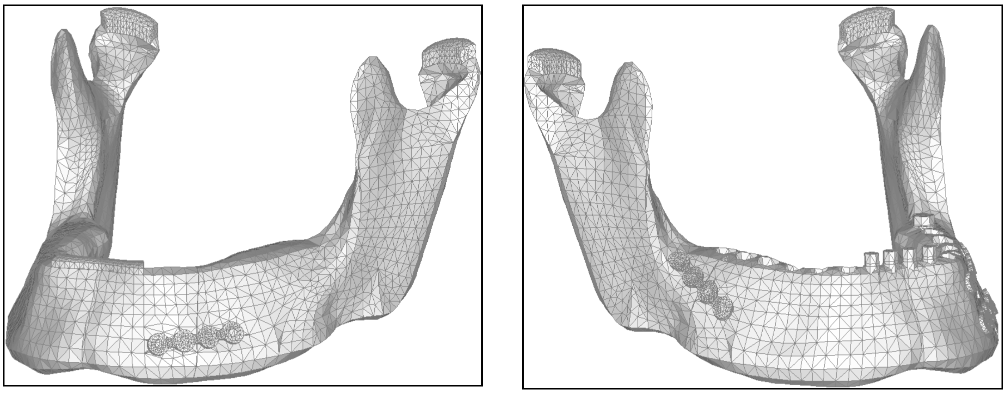

Fig. 4. Numerical models of two miniplate fixations in human mandible

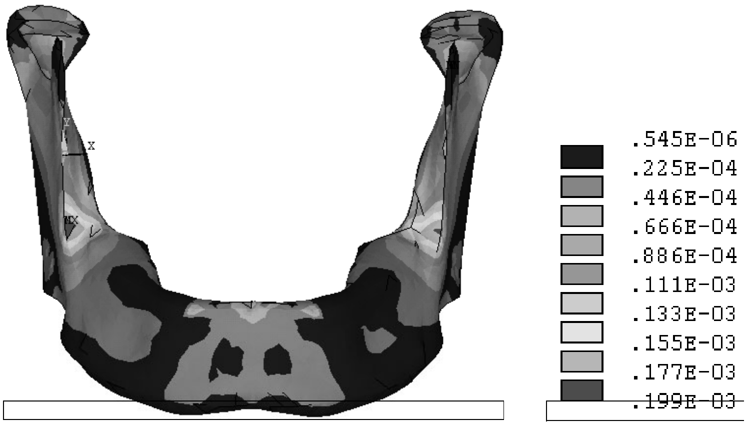

Fig. 5. Distribution of principal strain ε_1 in healthy mandible

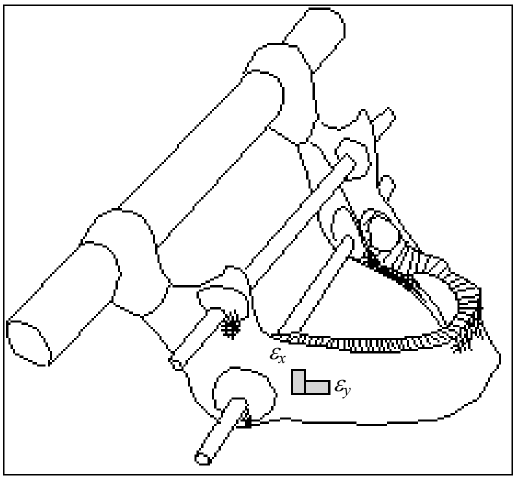

Fig. 6. Settlement of virtual strain gauge areas
for analysing the components of ε_x and ε_y strains

i.e., 7% and 8%, respectively, for ε_x and ε_y strain components. In the cases of broken mandible, the differences are relatively much higher, particularly for ε_y strain component, reaching even 40%. For ε_x strain component the differences approach respectively 18% and 16% for one-side and mutual fractures.

In our opinion, the divergences in FEM and ESPI results appear mainly due to the different ways of miniplate fixation in both experiments (numerical and speckle interferometry) and due to lack of modelling callus volume in laboratory experiment, while in the numerical simulations that element has been considered.

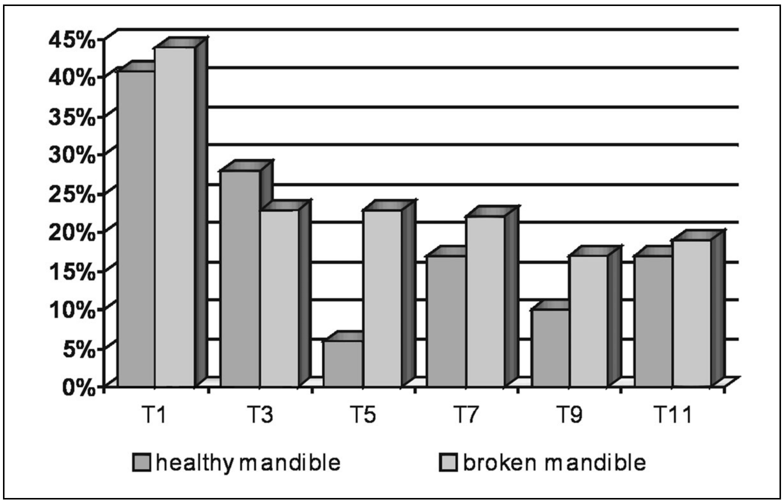

Fig. 7. Differences in strain values in chosen areas of mandible
calculated numerically and in strain gauge tests

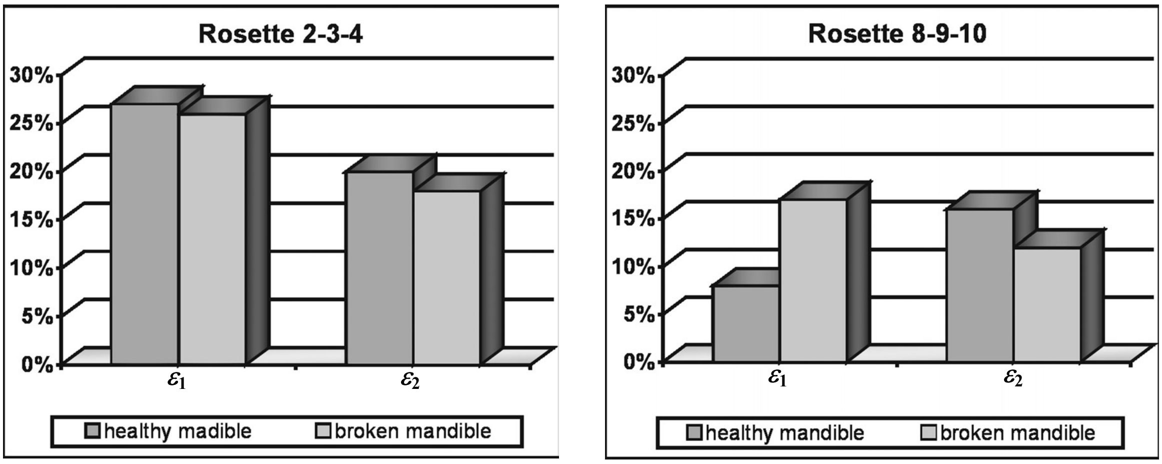

Fig. 8. Differences in principal strain values for strain gauges and FEM calculations for rosettes

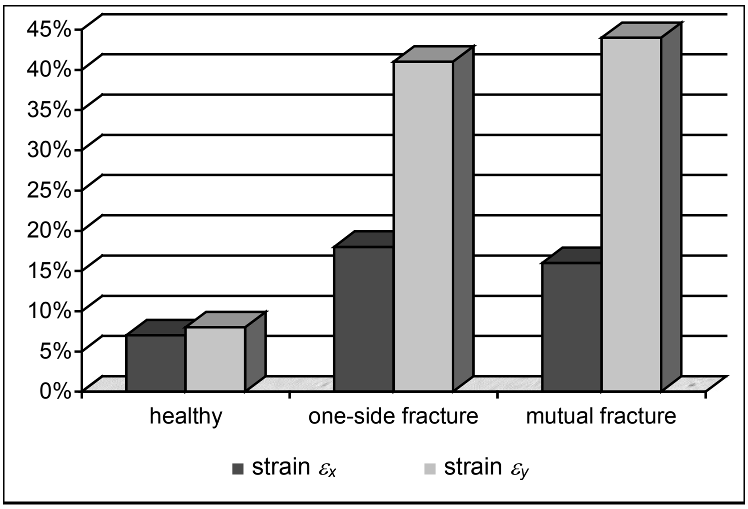

Fig. 9. Differences between ESPI results and strain values
calculated in numerical simulations

Table 1. Comparison of strain values from strain gauge experiments and FEM calculations for separate sensors

Strain gauge number	Healthy mandible strain [$\times 10^{-6}$]		Broken mandible strain [$\times 10^{-6}$]	
	Strain gauge	FEM analysis	Strain gauge	FEM analysis
T1	–24	–41	–23	–41
T3	60	83	67	87
T5	–15	–16	17	22
T7	–24	–29	–28	–36
T9	79	88	53	64
T11	36	30	32	26

Table 2. Comparison of strain values from strain gauge experiments and FEM calculations for rosettes

Rosette number	Healthy mandible			
	Strain ε_1 [$\times 10^{-6}$]		Strain ε_2 [$\times 10^{-6}$]	
	Strain gauge	FEM analysis	Strain gauge	FEM analysis
2–3–4	94	129	–60	–48
8–9–10	171	158	–25	–21
Rosette number	Broken mandible			
	Strain ε_1 [$\times 10^{-6}$]		Strain ε_2 [$\times 10^{-6}$]	
	Strain gauge	FEM analysis	Strain gauge	FEM analysis
2–3–4	130	175	–60	–49
8–9–10	153	185	–22	–25

5. Conclusions

1. The compatibility of the results of both experimental methods, i.e., ESPI and strain gauges, with the results of numerical calculations by means of FEM proves that the assumption taken into account when creating the numerical model was valid.

2. On the other hand, the divergence in the results obtained in each separate experimental and numerical experiments could be induced by:

• Simplification in modelling temporal-mandibular joint in laboratory experimental tests (in-plate pivot of one degree of freedom) which results in overrigidity of mandible, particularly in the areas of mandibular ramus and condylar process. In numerical calculations, an elastic element representing joint disc was modelled which improved the mobility of mandible.

• Simplified ways of modelling mandibular muscles in the areas of their attachments as well as the directions and values of their activities.

• Methods of miniplate fixation with screws in both types of laboratory experiments, while in numerical simulations that junction was modelled on common nodes which eliminated mutual mobility of mandible and miniplate.

• Possible errors in the way of assuming constrains in the area of anterior teeth in both laboratory experiments and numerical model.

References

[1] BARTKOWSKI S., (editor), *Chirurgia szczękowa*, Wydawnictwa Collegium Medicum UJ, Kraków, 1996.

[2] OSBORN J.W., *Features of human jaw design which maximize the bite force*, Journal of Biomechanics, 1996, Vol. 29, No. 5, 589–595.

[3] CHLADEK W., *Systemy modelowania wybranych stanów mechanicznych żuchwy ludzkiej*, Zeszyty Naukowe Politechniki Śląskiej, Gliwice, 2000.

[4] KROMKA M., *Analiza wytrzymałościowa osteosyntezy mini- i makropłytkowej urazów żuchwy*, PhD thesis, Kraków, 2006.

[5] HÄRLE F., CHAMPY M., TERRY B.C., *Atlas of Craniomaxillofacial Osteosynthesis*, Thieme, Stuttgart–New York, 1999.

[6] KROMKA M., MILEWSKI G., BĘDZIŃSKI R., ŚCIGAŁA K., *Application of speckle holographic interferometry in miniplates osteosynthesis of mandibular fractures*, 22nd Danubia–Adria Symposium on Experimental Methods in Solid Mechanics, 2005, 118–119.