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REVIEW PAPER

Finite Element Analysis: A Maxillofacial Surgeon's Perspective

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Abstract The science of finite element analysis (FEA) is purely a mathematical way of solving complex problems in the universe. In medical field, this is an innovation in biomedical research and development, as it gives easier mathematical solution to biological problems. This article deals with the understanding of various basic material properties of bone like Young's modulus, yield strength, Bulk modulus, shear modulus, Poisson's ratio and density from a maxillofacial surgeon's perspective. Basic concepts in FEA, its application, advantages, disadvantages, and limitations in the field of maxillofacial surgery have been discussed. The importance of surgical fraternity to be in coordination with evolving technologies has been emphasized for the future of evidence based practice of oral and maxillofacial surgery.

Keywords Biomedical finite element modeling and analysis · Material properties of bone · Finite element analyzes in maxillofacial surgery

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Introduction

FEA is an abbreviation for finite element analysis. This science is purely a mathematical way of understanding & solving complex problems in the universe. In medical field, this is an innovation in biomedical R&D, as it gives easier mathematical solution to biological problems. This article describes the basics of Finite element method (FEM) and it's applications in oral and maxillofacial surgery.

In medical science, we deal with body fluids, their components, gases, blood vessels, muscles, tendons, ligaments, cartilage, and bone. Further we can classify each into different subdivisions. Bone can be cortical or cancellous; muscle can be skeletal, smooth or a cardiac variety. Any solid, liquid, or gaseous matter, if existing in this universe, it exists only because of the virtue of its inherent properties of the components of which it is made of. That is, liquids (water/blood), have their own physical properties e.g., viscosity, but in varying values. Solids (metal, stone, wood, bone) in the same way differ in their material properties like elasticity or strength. Any matter existing, is also interdependent on other matter around. Action of each, has an equal and opposite reaction to each other. For example, mandible (a solid matter) is always surrounded by masticatory muscles and contraction and relaxation of the masticatory system (stress) produces a lot of strain in the mandible. The inherent properties of the mandible (elasticity and density) and vector (magnitude and direction) of the masticatory forces produced by the masticatory system not only influences the patterns of distribution of occlusal load or patterns of fracture but also has a lot of biomechanical effects which cannot be understood completely by in vivo studies [1, 2].

If suppose we want to calculate the effect of shear, compressive, or tensile forces (stress–strain analysis, displacement or deformation) on a known material of simple dimensions like square or circle the problem becomes simple. The analysis of the problem is simpler and solution to the problem obtained easily. But, the maxillofacial skeleton being complex in both its micro and macro structure, material properties and physical conditions at different areas of a single bone differ considerably [3, 4]. The complexity of the problem hence arises when the dimensions as well as the properties of the material get complex, making the analysis of the effects produced more complex and the solution is a difficult one to obtain. Hence, in FE modeling, the complex dimensions are first divided into smaller and simpler dimensions (like square, triangle, or a hexagon). The complex problem hence, is then made simple by converting it into a mathematical one, broken down into or shrunk into simpler problems using differential equations and then analyzed using analytical or numerical methods. The solution is thus obtained. The numerical method of obtaining the solution of a complex problem is called FEM. FEM allows detailed visualization of where structures bend or twist, and indicates the distribution of stresses and displacements. Hence, precise modeling of the craniofacial skeleton is of utmost importance. More you divide a complex model into known number of elements, dimension becomes simpler. More you divide a complex problem, analysis becomes easier. Hence, more the number of elements, simpler become the problem. Though the number of calculations increases, the results get more accurate. The accuracy of the results indicate a better understanding of the problem and hence serve as a important tool for the justifications of what we do, why we do and how do we do. These complexities cannot be evaluated by other studies and hence the need of FEA.

Creation of a FEA Model

A FEA model as discussed is a digital representation of an original material. If we are speaking about bone, with respect to mechanical engineering, it is considered only as a solid material just like any other metal or wood. There are certain properties for a solid which are inherent to the material. Only on applying these properties we can create a 3D finite element computer model for analysis.

Step 1 Acquiring Material Properties

In order to replicate the original material on to the computer, we need to know the properties of the material so as to reconstruct the same. When we want to analyze the effect of a known amount of force on a material (stress, i.e., force per unit area); we need to understand that there will be change in the geometry of material when this stress is applied on it. This deformation of the material is called strain, which is proportional to the stress up to a limit and is dependent on the material properties.

In FEM, we need to consider bone basically as a solid and to create its FE model we need to know it is basic material properties like Young's modulus of elasticity and yield strength, Bulk and Shear modulus, Poisson's ratio, and density to increase the accuracy of the finite element analysis.

Young's Modulus of Elasticity and Yield Strength

Elasticity is the ability of a material to return to its previous state after the applied stress is removed. If the amount of strain produced in the material is directly proportional to the stress applied on the material, such materials are called linearly elastic materials where stress applied is uniformly spread all throughout the body of the material. When this relation is plotted on the graph we get a linear slope (Fig. 1), which is a representation of linear stress called as Young's modulus of elasticity [5]. Imagine mandible subjected to pulling forces in two different directions due to elevator and depressor group of masticatory muscles. Hence, by knowing the Young's modulus of mandible we can calculate the change in dimension of mandible (how much it extends under tension or gets compressed under compression simultaneously) at different points in the mandible.

Young's modulus is used to determine stress–strain relationships in a linearly elastic portion of a stress strain curve and is always below the yield point, beyond which the material starts to deform. Most of the linearly elastic materials retain some amount of deformation even after the

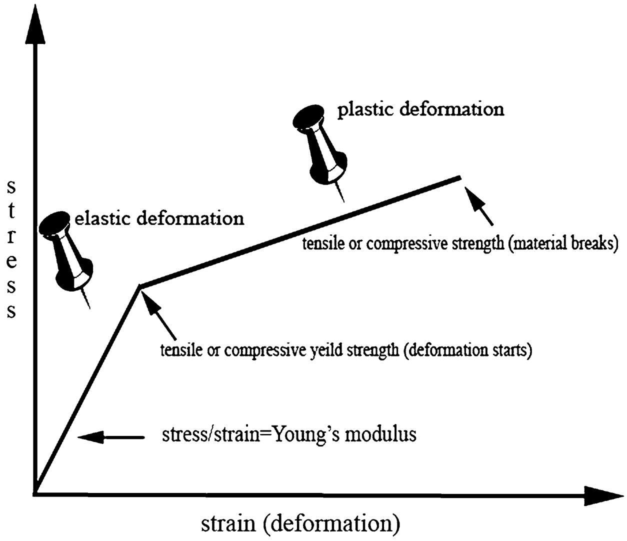

Fig. 1 Stress–strain curve

stress applied is removed. This is called as the plasticity of the material. If the stress applied is still not removed, the material completely deforms or it completely fails to regain its previous shape. This point is called as failure [yield strength—minimum amount of stress (Force/Unit area) required for the permanent deformation (failure) of a material (example, fracture of bone)]. If this failure occurs because of compressive or tensile stresses applied, then it is called as compressive or a tensile failure, respectively. Imagine pulling a rubber band where it first gets stretched (elasticity), then slightly loses its shape beyond the yield point (plastic deformation) and further gets cut at the point of failure. In case of brittle materials, the material beyond the yield point directly undergoes failure (breaks) without going through a phase of plastic deformation.

Bulk Modulus

Bulk modulus describes the material's response (resistance) to uniform pressure (Fig. 2). The response of a cricket/tennis/rubber ball getting compressed uniformly from all directions (when squeezing) is described by the Bulk modulus of the material of cricket/tennis/rubber ball. Bone too is subjected to uniform pressure during many conditions (imagine mastication). The response of the bone to uniform pressure applied on it is described by the Bulk modulus of the bone (different for cortical, cancellous, and osteoporotic bone).

Shear Modulus

Imagine a fracture of the symphysis of mandible, where there is tension in the superior border, compression in inferior border and shear in between. Shear modulus quantifies the material's response to shearing strain and is concerned with the deformation of a solid when it experiences a force parallel to one of its surfaces while its opposite face experiences an opposing force (friction) (Fig. 3).

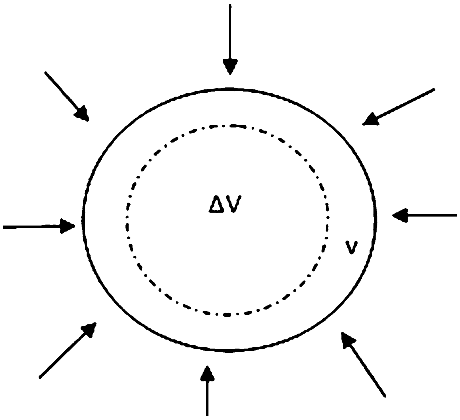

Fig. 2 Bulk modulus, *V* original volume before stress; *ΔV* change in volume after stress; *arrow* direction of force vector

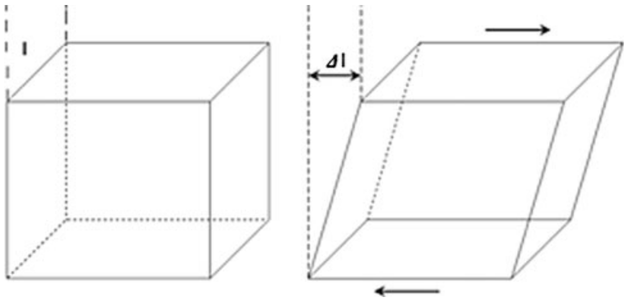

Fig. 3 Shear modulus, *l* original length before shear stress; *Δl* deformation after shear stress; *arrow* direction of force vector

Poisson Ratio

When a material is stretched in one direction it tends to get thinner in other two directions (vice versa). This is called as Poisson effect (Fig. 4). Poisson ratio is the ratio of the relative contraction strain (transverse strain) perpendicular to applied load to relative extension strain (axial strain) parallel to applied load. On the molecular level, Poisson effect is caused by slight movements between molecules and the stretching of molecular bonds within material lattice to accommodate the stress. When the bonds elongate in the direction of load, they shorten in the other two directions. This behavior multiplied millions of times throughout the material lattice is what drives the phenomenon.

Poisson effect has a considerable influence in pressurized pipes (imagine blood vessels). When the air/liquid inside a pipe is highly pressurized, it expands due to a uniform force on the inside of the pipe, resulting in a radial stress (along the length of pipe) within the pipe material. Due to Poisson's effect this radial stress will cause the pipe to slightly increase in diameter and simultaneously decrease the length of the pipe.

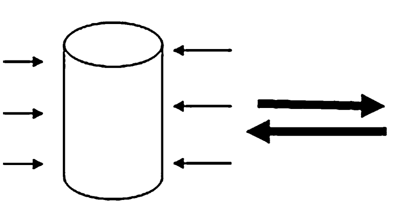

Fig. 4 Poisson effect, *arrow* direction of force vector

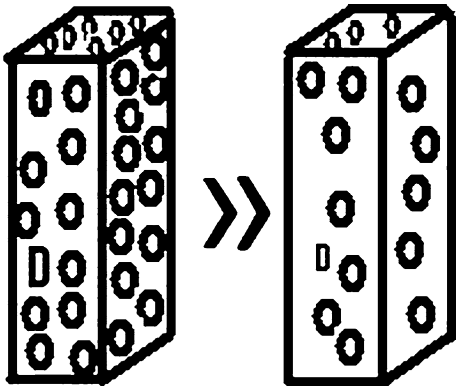

Fig. 5 Density, ($D > D$) where *D* solid with more compactly arranged molecules; *D* solid with less compactly arranged molecules; *open circle* symbolic representation of a molecule of solid

Density

Density of a material is basically an indication of compactness of a material based on how dense its micro structural arrangement is at a molecular level (Fig. 5). This is the basic need for assessment of the strength of a material which directly or indirectly affects all other material properties. Bone tissue, as with all biological tissue, is neither homogeneous nor isotropic. That is, the physical properties of bone vary both in location and in direction.

Step 2 Designing

For designing a 3D computer model mimicking the original, we need high technical expertise. More accurate the model is, more reliable is the result of analysis. Hence, 3D modeling of materials is important for successful studies. The maxillofacial skeleton being even more complex demand for accuracy of modeling naturally is more. This modeling of biological tissues can be done in two ways. In the first, CT scan of the concerned area of interest is taken (axial and coronal 1 mm slices) and using the geometry of the bone and surrounding structures, dimensions and inter point measurements are noted. With these data a 3D model is constructed as accurate as possible. But this entire process needs lot of time, depending upon the available technical assistance. The other way of modeling is using commercially available softwares which would give you not only a 3D model but also meshed finite element model, just by using CT scan images in DICOM format, saving lot of time and needs less technical expertise.

Step 3 Creation of a FEA Model

We all know that any matter, for instance, a piece of bone or metal can be cut into infinite number of pieces, if such a blade is provided, with each of the pieces exhibiting the same characteristics of that of the original bone/metal. If we precisely rearrange those pieces back into their same place, we can get back the complete bone/metal.

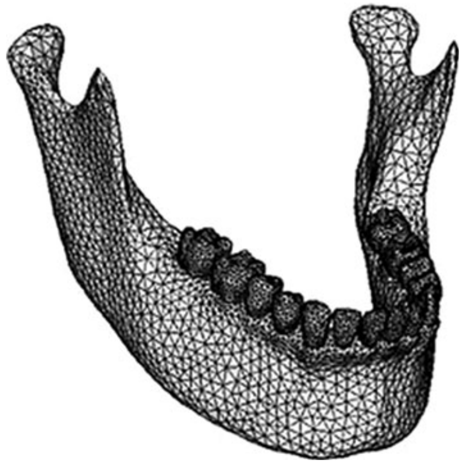

Fig. 6 Three dimensional finite element meshed model of human mandible

Once the 3D model is prepared, depending on the study and accuracy intended, it is then meshed (single complex 3D mandible is divided using softwares into simpler dimensions). Each mesh consists of varying number of nodes depending upon the shape of element (triangle/hexagon) (Fig. 6) [6].

Step 4 Finite Element Analyzes

After creating a 3D computer model of a bone/metal by reconstructing and mimicking the original, this computer model created is called as the component. This model is then cut using finite element softwares into finite number of smaller sections called elements and this model with finite number of elements is called as the finite element model, with each element having properties exactly as the original material. The natural physical conditions (could be force, temperature etc.) around the original (bone/metal), are applied on these finite number of elements of the FEA model using softwares. The results are analyzed (hence FEA) using solver softwares which are built for solving complex problems (in our case, complex biomechanical engineering problems of craniofacial skeleton). The software uses and applies the exact physical information that is actually present in the reality (muscle/occlusal/impact force, temperature), mimics situations and analyzes what happens (deformation) in the mimicked original model on the computer virtually (static/dynamic analysis), providing results with high degree of accuracy. Hence FEA is basically a reconstruction of stress, strain, and deformation in digital structure.

Structural analysis comprises the set of physical laws and mathematics required to analyze and predict the behavior of structures, whose integrity is judged largely based upon their ability to with stand loads; they commonly include buildings, bridges, aircraft, ships, and cars. In medicine, structural analysis incorporates the fields of mechanics and dynamics to analyze biological tissues. From a theoretical perspective the primary goal of structural analysis is the computation deformations, internal forces and stresses. In practice, structural analysis can be viewed more abstractly as a method to prove the soundness of a design without a dependence on directly testing it. The finite element approach of structural analysis is an advanced matrix algebraic method to model an entire structure with one-, two-, and three-dimensional elements [6].

Advantages of FEM

1. The finite element technology is now sophisticated enough to handle just about any system as long as sufficient computing power is available. Its applicability includes, but is not limited to, linear and nonlinear analysis, solid and fluid interactions, materials that are isotropic, orthotropic, or anisotropic, and external effects that are static, dynamic, and environmental factors.
2. With FEA we can virtually simulate almost every model for the exact pre, intra and post operative behavior, as if it is in reality. Thus the result reliability is high and stands unchallenged.
3. FEA techniques have resulted in substantial cost reduction in the cases needing very expensive stereo lithographic models for presurgical planning.
4. With FEA simulation, “time” has been saved drastically in analysis process. The projects, which used to take months and years to leave the R&D walls, are now saving 60–80% time reduction with FEA.

Disadvantages of FEM

1. Inaccurate data, information, and interpretation will yield totally misguiding results.
2. Modeling human structures is extremely difficult because of their complex anatomy and lack of complete knowledge about their mechanical behaviors. Certain assumptions are bound to be accepted. Hence results will depend on the personnel involved in the process.

Applications of FEM in Oral and Maxillofacial Surgery

1. In cranio-maxillofacial trauma
    a. For impact analysis [7, 8].
    b. Optimal localization and direction of different osteosynthesis devices [9].
    c. Analysis of loads across a fracture and the magnitude and direction of force on osteosynthesis [10].
2. In orthognathic surgery
    a. Biomechanical analysis of different osteotomy designs in orthognathic surgery [11].
    b. Evaluating soft tissue changes in a 3D plane after aesthetic and reconstructive surgeries of the face [12].
3. In maxillofacial pathological resection and reconstructive surgery for designing biomechanically stable osteotomy cuts by using design principles during osseous resections and also to study the biomechanics of reconstructed mandible [13–15].
4. In dental implantology to study the influence of design of dental implant on distortion and stresses acting on implant and the surrounding bone [16, 17].
5. In distraction osteogenesis for biomechanical evaluation distraction osteogenesis of craniofacial skeleton [18, 19].

Conclusion

Finite element method in maxillofacial surgery as a whole involves two processes:

a) FEA models simulating surgeries/impacts/osteosynthesis.
b) Biomechanical analysis and interpretation of results of the simulations.

Reviewing the literature, one can find a drastic change in the mindset or the perspective of the maxillofacial surgeon of the recent past to the present, in approaching the situation, be it any kind of maxillofacial surgery. The future of maxillofacial surgery is purely evidence based. Innumerable queries of the past have been answered by the present researchers using modern technology. Many theories have been disproved and many hypotheses have become theories. We notice that the treatment plan of the same problem (e.g., mandibular fracture) has been widely differing from the past to the present and is bound to change in the future [20–23]. This change will be a result of how well we understand our problem. This understanding demands the surgical fraternity to work hand in glove with evolving technologies and adapt to the changes frequently, as this is the only way for the future of evidence based practice of maxillofacial surgery.

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