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# Finite Element Analysis: Basics And Its Applications In Dentistry

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**Abstract**

**Objectives:** The purpose of this review article is to address the basics of finite element analysis and its application in dentistry.

**Material and Methods:** Literature was selected through a search of PubMed, Embase and Cochrane electronic databases. The keywords used for search were finite element analysis; finite element analysis in dentistry; finite element analysis dental; finite element analysis dental implant. The search was restricted to English language articles related with the basics of finite analysis method and its application in dentistry.

**Results:** Steps in the solution procedure using finite element analysis, applications of the method in general and in dentistry including limitations were discussed. During last few decades, the application of a well proven predictive technique i.e. finite element analysis has revolutionized dental and biomedical research. Finite element analysis consists of a computer model of a material or design that is stressed and analyzed for specific results. Finite element methods are predominantly used to perform analysis of structural, thermal and fluid flow situations. Finite element analysis has also been applied to the description of changes of physical form in biologic structures.

**Conclusions:** Finite element analysis is one of the most widely used engineering analysis techniques in the world today. Finite element method which is an engineering method of calculating stresses and strains in all materials including living tissues has made it possible to adequately model the tooth and it's supporting structures for scientific checking and validating the clinical assumptions. Finite element analysis is used in all fields of dentistry especially in implant dentistry.

**Key Words**
finite element analysis; stress analysis, dental; dentistry.

## Introduction

The principal goal of dentistry is to maintain and improve the quality of life of the dental patients. This goal can be accomplished by preventing diseases, relieving pain, improving masticatory efficiency, enhancing speech and improving appearance. As many of these objectives require the replacement or alterations of the existing tooth structure, the main challenges for the centuries have been the development and selection of biocompatible materials that can withstand the unique conditions of the oral environment.

In recent years, dentistry has witnessed the introduction and subsequent withdrawal of numerous unsatisfactory products and techniques from the market. The failure of various products and techniques is mainly because of unique conditions of oral environment. These failures make the researchers to investigate relationship between laboratory research and clinical performance of the techniques and materials. So, all the laboratory or in-vitro studies should be done keeping the oral environment in mind [1].

Classical methods of mathematical stress analysis are extremely limited in their scope and are inappropriate for dental structures that have an irregular structural form and complex loading [2]. The finite element is a modern technique of numerical stress analysis that has the great advantage of being applicable to solids of irregular geometry and heterogeneous material properties. It is therefore ideally suited for the examination of structural behavior of the oral cavity.

The Finite element analysis (FEA) can be applied to many areas in engineering, biomedical engineering is among one of them. The development in main frame computers and availability of powerful microcomputers has brought this method within the reach of students and engineers. FEA is used in all fields of dentistry especially in implant dentistry [3]. The aim of this review article is to address the basics of FEA and its application in dentistry.

## Material And Methods

Literature was selected through a search of PubMed, Embase and Cochrane electronic databases. The keywords used for search were finite element analysis; finite element analysis in dentistry; finite element analysis dental; finite element analysis dental implant. The search was restricted to English language articles related with the basics of finite analysis method and its application in dentistry.

## History of FEA

The FEA originated from the need for solving complex elasticity and structural analysis problems in civil and aeronautical engineering. Its development can be traced back to the work by Alexander Hrennikoff [4] and Richard Courant [5]. The roots of the theory relates back to the Ritz method of numerical analysis, first introduced in 1909 [6]. Further development of these ideas continued through the 1940's and 50's. By 1953, engineers began to use computers to solve structural problems.

Development of the FEA began in earnest in the middle to late 1950's for airframe and structural analysis. It gathered momentum at the University of Stuttgart through the work of John Argyris [7] and at Berkeley through the work of Ray W. Clough [8] in the 1960s for use in civil engineering. In 1963, FEA was recognized as a specific technique, and a serious academic discipline. With the advent of personal-computers in the 1980's, the methods have become more widely used. It is now possible for engineers in virtually every industry to take advantage of this powerful tool.

**Steps in the solution procedure using FEA**

1. Discretization of problem
2. Imaging
3. Meshing
4. Boundary conditions
5. Types of solutions

**Discretization of problem**

Solving a real life problem with continuous material approach is difficult and the basic of all numerical methods is to simplify the problem by discretizing (discontinuation) it. In simple words, nodes work like atoms with gap in between filled by an entity called as element [9,10]. Calculations are made at nodes and results are interpolated for elements. There are two approaches to solve any problem:

1. Continuous approach (all real life components are continuous).
2. Discrete approach (equivalent mathematical modeling).

All the numerical methods including finite element follow discrete approach. Meshing (nodes and elements) is nothing but discretization of a continuous system with infinite degree of freedoms to finite degree of freedoms [9].

**Imaging**

a) *Imaging and three-dimensional reconstruction.* Recent innovations in computerized tomography (CT), magnetic resonance imaging (MRI), and confocal microscopy have revolutionized biological imaging. It is now possible to capture serial sections of virtually any structure and generate exquisitely detailed three-dimensional reconstructions. Three-dimensional surface reconstructions created from CT scans are used as templates for three-dimensional finite element models. Initial three-dimensional surface reconstructions are typically quite rough and require significant editing before they can be imported into a FE tool and successfully meshed as a finite element model [11].

b) *Image processing: editing the three-dimensional image.* Editing three-dimensional images is the most time intensive step in building FE models of biological structures. The ultimate goal of three-dimensional image processing is to generate a "water-tight" surface model that can be imported into and successfully manipulated in FE software.

The most important aspect of the simplification process of three-dimensional images involves smoothening and removing details in selected areas of the model. three-dimensional surface representations are composed of connected polygons and are often referred to as 'polygon models'. The more polygons a model contains, the greater is its fidelity to the object it represents and the larger is its size. Image processing is the most labor-intensive aspect of conducting FE analyses of biological structures [11] **(Figure 1 and Figure 2).**

**Meshing**

FEM uses a complex system of points (nodes) and elements, which make a grid called as mesh. Basic theme of FEA is to make calculations at only limited (finite) number of points and then interpolate the results for entire domain (surface or volume). Any continuous object has infinite

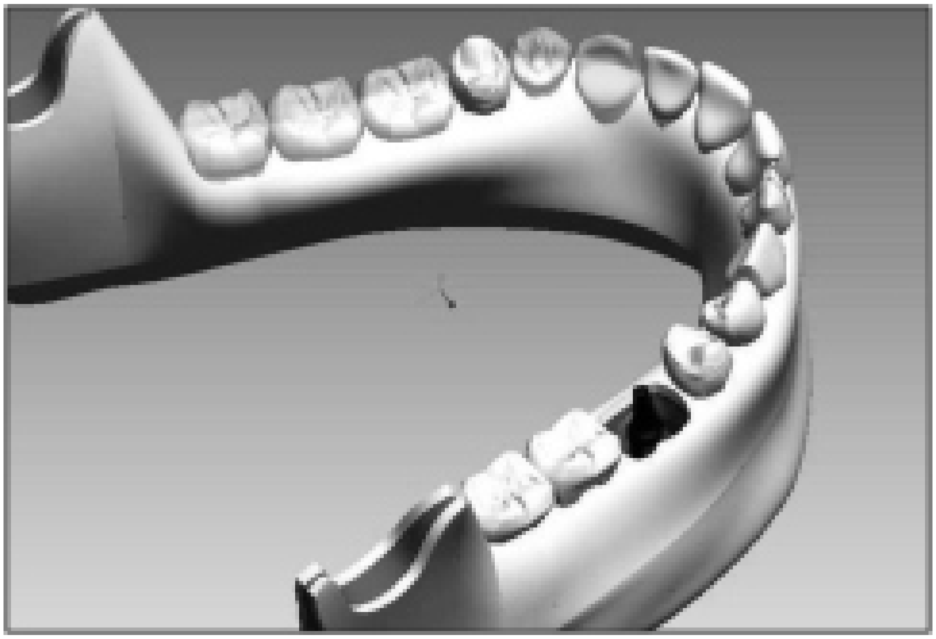

**Fig 1: CAD image of an implant placed in mandible.**

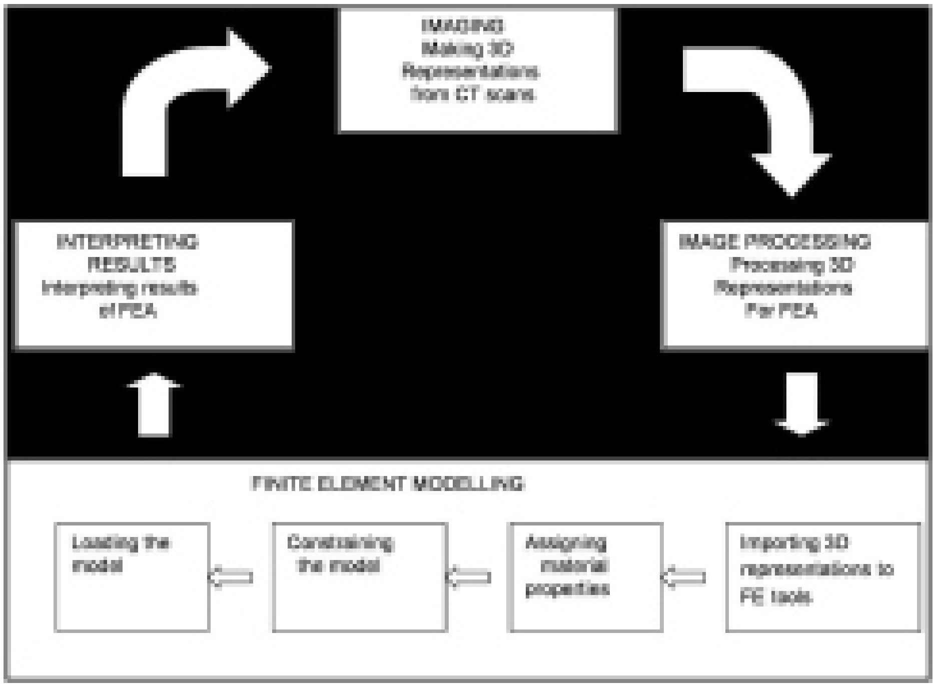


**Fig 2: Steps in FEA**

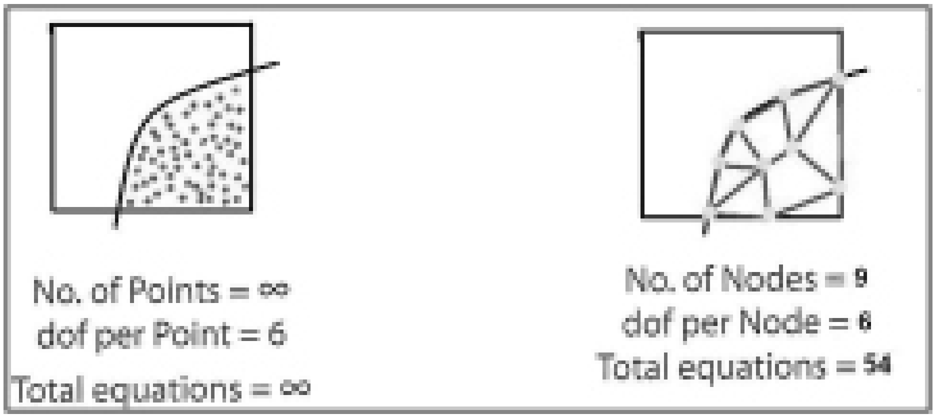


**Fig 3: Meshing**

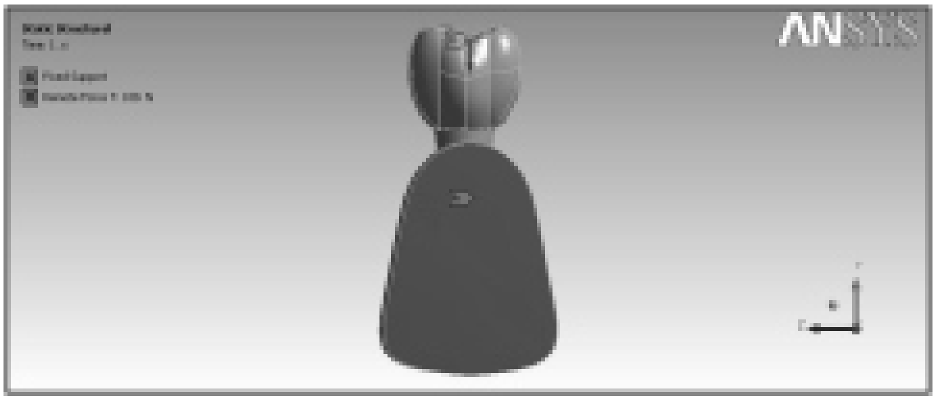


**Fig 4: Boundary conditions**

**Table 1. Mechanical properties used for different structures**

| 0. | Material | Elastic modulus (E) (MPa) | Poisson's ratio |
|---|---|---|---|
| 1. | Isotropic enamel | 80000 | 0.3 |
| 2. | Dentin | 18,600 | 0.31 |
| 3. | Cementum | 18,600 | 0.31 |
| 4. | Dental pulp | 2.07 | 0.45 |
| 5. | Periodontal ligament | 50 | 0.49 |
| 6. | Spongy bone | 345 | 0.3 |
| 7. | Compact bone | 13,800 | 0.26 |
| 8. | Titanium | 1,10,000 | 0.350 |
| 9. | Porcelain | 70,000 | 0.190 |
| 10. | Cement | 12,000 | 0.25 |
| 11. | Cobalt-Cromium metal | 87,900 | 0.35 |

degrees of freedom and it is just not possible to solve the problem in this format. FEA reduces degrees of freedom from infinite to finite with the help of discretization i.e. meshing (nodes and elements) as shown in **Figure 3** [9].

**Two-dimensional meshing and three-dimensional meshing**

Two-dimensional modeling is comparatively simple and it allows the analysis to be run on a relatively normal computer, but it also sometimes tends to yield less accurate results. For two-dimensional analysis, the element shapes are triangular, quadrilateral, and in three-dimensional analysis element shapes are tetra, penta, hex and pyramid. Three-dimensional modeling produces more accurate results, but it can run only on the fastest computers effectively [9].

**Boundary conditions**

Boundary condition is application of force and constraint. Different ways to apply force and moment are concentrated load (at a point or single node), force on line or edge, distributed load (force varying as equation), bending moments and torque (**Figure 4** shows boundary condition).

After fixing the boundary conditions the software is run for determining stresses & strains using linear static analysis & non linear analysis [9].

**Types of solutions**

The above analysis is done to assess the stresses acting upon the materials during function in the oral cavity by applying various material properties **(Table 1)** [12-14]. These stresses are:

1. Normal or principal stress: acts perpendicular to the cross section and causes elongation or compression.
2. Shear stress: acts parallel to the cross section and causes distortion (changes in original shape).

Whenever an elastic body is subjected to loads in its 3 dimensions, the stresses will get developed along the principal axis of the body. These are the principal stresses. There are three "principal stresses" that can be calculated at any point, acting in the x, y, and z directions. These stresses should not exceed the yield stress of the material.

There is a convention on listing the three principal stresses which makes the 'first' one the maximum of the three, and the 'third' one the minimum, which can be the maximum compressive (negative) stress, but may actually be a positive stress.

Maximum principal stress. The maximum principal stress gives the value of stress that is normal to the plane in which the shear stress is zero. The maximum principal stress helps you understand the maximum tensile stress induced in the part due to the loading conditions **(Figure 5).**

Minimum principal stress. The minimum principal stress acts normaly to the plane in which shear stress is zero. It helps you to understand the maximum compressive stress induced in the part due to loading conditions **(Figure 6)**.

Von Mises stress. The von Mises criterion is a formula for calculating whether the stress combination at a given point will cause failure.

The von Mises criterion is a formula for combining three principal stresses into an equivalent stress, which is then compared to the yield stress of the material **(Figure 7)**. The yield stress is a known property of the

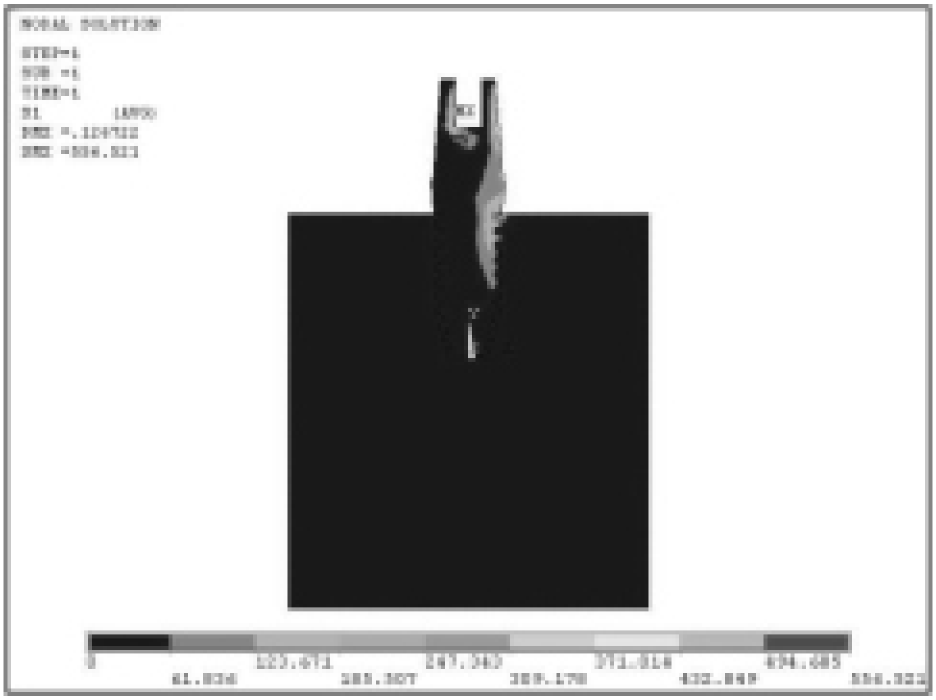

Fig 5: 2-D FEA Effect of tensile load around implant

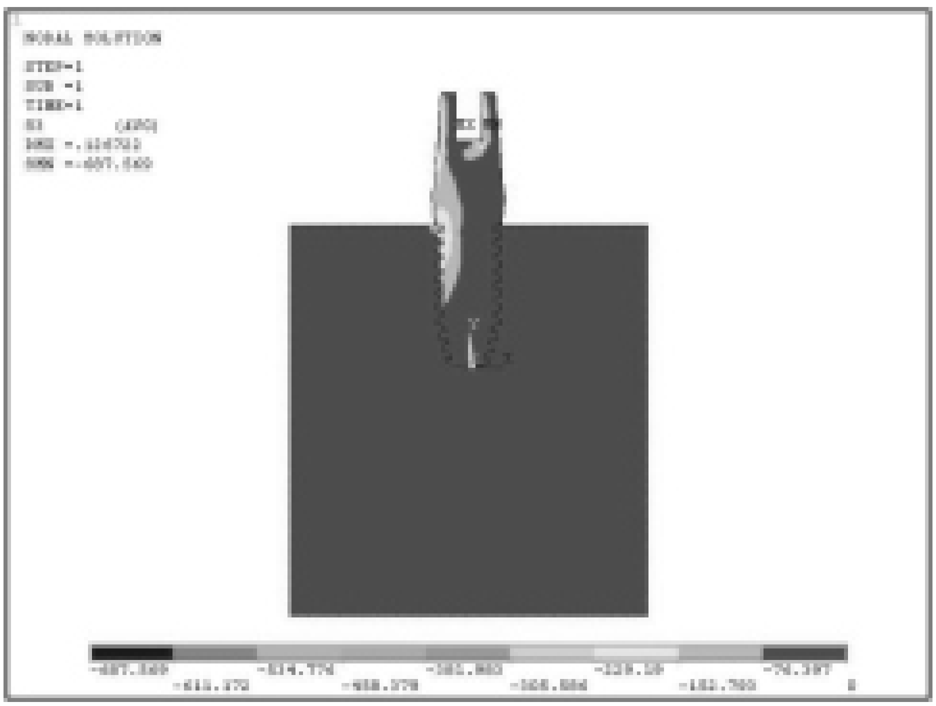

Fig 6: 2-D FEA Effect of compressive load around implant

material and is usually considered for the failure stress. If the "von Mises stress" exceeds the yield stress, then the material is considered to be at the failure condition. The von Mises theory is used for ductile materials such as metals and evaluates stresses in both static and dynamic conditions [7,8].

**Applications of finite element analysis**

FEA makes it possible to evaluate a detailed and complex structure in a computer, during the planning of the structure. The demonstration in the computer of the adequate strength of the structure and the possibility of improving the design during planning can justify the cost of this analysis work. FEA has also been known to increase the rating of structures that were significantly overdesigned and built many decades ago.

In the absence of FEA (or other numerical analysis), development of structures must be based on hand calculations only. For complex structures, the simplifying assumptions required to make any calculations possible can lead to a conservative and heavy design. A considerable factor of ignorance can remain as to whether the structure will be adequate for all design loads. Significant changes in designs involve risk. Designs will require prototypes to be built and field tested. The field tests may involve expensive strain gauging to evaluate strength and deformation.

With FEA, the weight of a design can be minimized, and there can be a reduction in the number of prototypes built. Field testing will be used to establish loading on structures, which can be used to do future design improvements via FEA [15].

**Applications of finite element analysis in dentistry**

- FEA has been applied for the description of form changes in biological structures (morphometrics), especially in the area of growth and development [16,17].
- The knowledge of physiological values of alveolar stresses is important for the understanding of stress related bone remodeling and also provides a guideline reference for the design of dental implants [18-21].
- FEA is also useful for designing and studying structures with inherent material homogeneity and potentially complicated shapes such as dental implants [22-25]. Analysis of stresses produced in the periodontal ligament under different loading conditions [26-29]. To study stress distribution in supporting structures of tooth in relation to different designs of fixed and removable prosthesis [30-33].To optimize the design of dental restorations [2,34,35]. To investigate stress distribution in tooth with cavity preparation and biomechanical preparation during root canal treatment [36,37].

The type of predictive computer model described may be used to study the biomechanics of tooth movement, whilst accurately assessing the effect of new appliance systems and materials without the need to go to animal or other less representative models.

**Software used for finite element analysis**

The various software used in FEA are Abaqus Explicit, Ansys, Dytran, Femfat, Hypermesh, Ls-dyna, Madymo, Magmasoft, MSC Nastran, Pro mechanica,

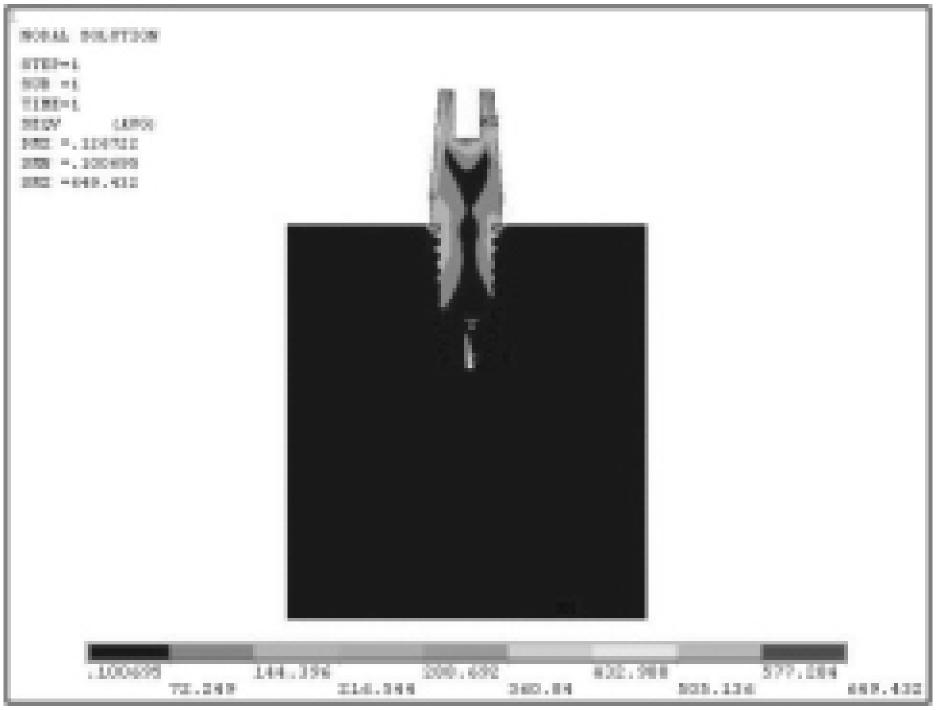

**Fig 7: 2-D FEA Vonmises stress around implant**

Star-CD, Tosca, Unigraphics, etc [38,39].

**Limitations of finite element analysis**

Finite elements methods are extremely versatile and powerful and can enable designers to obtain information about the behavior of complicated structures with almost arbitrary loading. In spite of the significant advances that have been made in developing finite element packages, the results obtained must be carefully examined before they can be used [9].

The most significant limitation of FEA is that the accuracy of the obtained solution is usually a function of the mesh resolution. Any regions of highly concentrated stress, such as around loading points and supports, must be carefully analyzed with the use of a sufficiently refined mesh. In addition, there are some problems which are inherently singular (the stresses are theoretically infinite). Special efforts must be made to analyze such problems [9,10].

An additional concern for any user is that because current packages can solve so many sophisticated problems, there is a strong temptation to "solve" problems without doing the hard work of thinking through them and understanding the underlying mechanics and physical applications. Modern finite element packages are powerful tools that have become increasingly indispensable to mechanical design and analysis. However, they also make it easy for users to make big mistakes. Obtaining solutions with FEA often requires substantial amounts of computer and user time. Nevertheless, finite element packages have become increasingly indispensable to mechanical design and analysis.

**Summary & Conclusion**

The finite element analysis is a relatively recent discipline that has quickly become a mature method, especially for structural analysis. The costs of applying this technology to everyday design tasks have been dropping, while the capabilities delivered by the method are expanding constantly. With education in the technique and in the commercial software packages becoming more and more available, the question has moved from "Why apply finite element analysis?" to "Why not?" The method is fully capable of delivering higher quality products in a shorter design cycle with a reduced chance of field failure, provided it is applied by a capable analyst. It is also a valid indication of thorough design practices, should an unexpected litigation crop up. The time is now for industry to make greater use of this and other analysis techniques.

It can be concluded that finite element analysis can be used in various fields of dentistry like Implant dentistry, Prosthodontics, Periodontics etc. to study the stress patterns related to structural behaviour of oral tissues.

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