1. INTRODUCTION

1.1. Preface

The finite element method is the most widely used numerical method for calculating mechanical structures, however they may be complete in terms of geometry, applications or materials.

The generality of the method, the simplicity of the basic concepts and the use of electronic computers, explains the expansion and interest in this method.

Currently, this method, is aided with multiple applications extremely varied. As a result of formulating concepts of maximum generalizations of this method, developed algorithms and computer programs applied in a field of engineering were subsequently transferred and adapted successfully without significant changes in other areas of applied research such as fluid mechanics phenomena heat and mass transfer, electromagnetism, mechanics, biomechanics, soil and rock mechanics, acoustics, technology and materials processing, etc. .

Like any numerical method of calculation, this is an approximate method thus provides approximate solutions that ensures sufficient accuracy for almost all engineering calculations .

The interest for this method is reflected by the increase in the number of scientific publications and conferences dedicated to this method. Important is the increasing the number of finite element computer programs. The most recent software applications dedicated for mechanical design have incorporated special software modules, which allows numerical analysis with the finite element method or by other methods [37].

1.2. About PLM, CAD / CAE / CAM

In industry, Product Lifecycle Management (PLM) is the process of managing the entire lifecycle of a product from its conception, through design and manufacture, to service and disposal. PLM integrates people, data, processes and business systems and provides a product information backbone for companies and their extended enterprise. Product lifecycle management can be considered one of the four cornerstones of a manufacturing corporation's information technology structure (Fig. 1). Within PLM there are five primary areas:

- Systems engineering (SE);
- Product and portfolio (PPM);
- Product design (CAx);
- Manufacturing process management (MPM);
- Product Data Management (PDM).

All companies need to manage communications and information with their customers (CRM - customer relationship management), their suppliers and fulfillment (SCM-supply chain), their resources within the enterprise (ERP-enterprise resource planning) and their product planning and development [24].

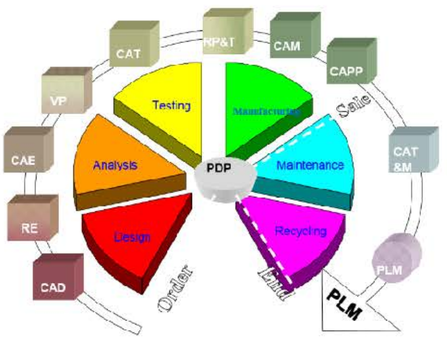


Fig. 1 The Product Lifecycle Management (PLM) cycle

The following picture (Fig. 2) shows where CAD/CAM/CAE systems are used within the overall product lifecycle, using the case of an automobile as an example [3].

Computer-aided design (CAD), also known as computer-aided design and drafting (CADD) is the use of computer technology for the process of design and design-documentation. Computer Aided Drafting describes the process of drafting with a computer. Computer-aided design (CAD) is the use of computer systems to assist in the creation, modification, analysis, or optimization of a design (Fig. 3). CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing. CAD output is often in the form of electronic files for print, machining, or other manufacturing operations [41].

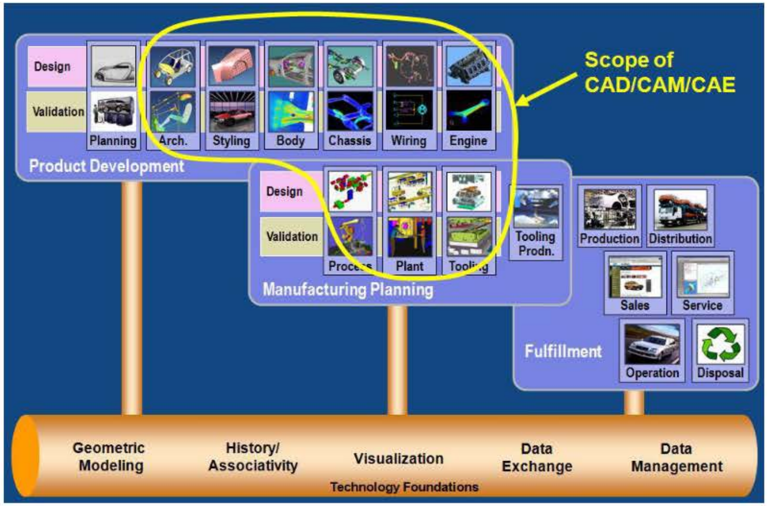


Fig. 2 Scope of CAD / CAE / CAM system in automotive [37]

Computer-aided design is used in many fields. Its use in electronic design is known as Electronic Design Automation, or EDA. In mechanical design is known as Mechanical Design Automation, or MDA, it is also known as computer-aided drafting (CAD) which describes the process of creating a technical drawing with the use of computer software. CAD software for mechanical design uses either vector based graphics to depict the objects of traditional drafting, or may also produce raster graphics showing the overall appearance of designed objects.

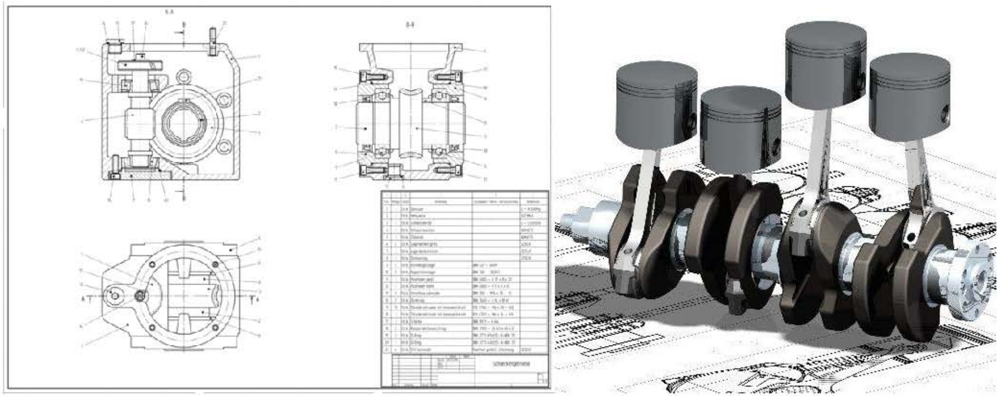


Fig. 3 Example 2D and 3D CAD drawing [20]

However, it involves more than just shapes. As in the manual drafting of technical and engineering drawings, the output of CAD must convey information, such as materials, processes, dimensions, and tolerances, according to application-specific conventions. CAD may be used to design curves and figures in two-dimensional (2D) space; or curves, surfaces, and solids in three-dimensional (3D) space (Fig. 3).

Computer-aided engineering (CAE) is the broad usage of computer software to aid in engineering tasks (Fig. 4). It includes computer-aided design (CAD), computer-aided analysis (CAA), computer-integrated manufacturing (CIM), computer-aided manufacturing (CAM), material requirements planning (MRP), and computer-aided planning (CAP) [33].

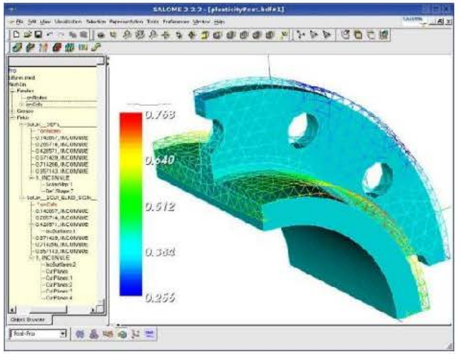


Fig. 4 Nonlinear static analysis of a 3D structure subjected to plastic deformations [21]

CAE involves to perform various types of analysis, measurements, tests, simulations on the model created using CAD (structural analysis, analysis of functioning electronic circuits in order to optimize its characteristics.

CAE areas covered include:

- Stress analysis on components and assemblies using FEA (Finite Element Analysis);
- Thermal and fluid flow analysis Computational fluid dynamics (CFD);
- Multibody dynamics (MBD) & Kinematics;
- Analysis tools for process simulation for operations such as casting, molding, and die press forming;
- Optimization of the product or process;
- Safety analysis of postulate loss-of-coolant accident in nuclear reactor using realistic thermal-hydraulics code.

CAE tools are very widely used in the automotive industry. In fact, their use has enabled the automakers to reduce product development cost and time while improving the safety, comfort, and durability of the vehicles they produce. The predictive capability of CAE tools has progressed to the point where much of the design verification is now done using computer simulations rather than physical prototype testing. CAE dependability is based upon all proper assumptions as inputs and must identify critical inputs (BJ).

Even though there have been many advances in CAE, and it is widely used in the engineering field, physical testing is still used as a final confirmation for subsystems due to the fact that CAE cannot predict all variables in complex assemblies (i.e. metal stretch, thinning).

Computer-aided manufacturing (CAM) is the use of computer software to control machine tools and related machinery in the manufacturing of workpieces. This is not the only definition for CAM, but it is the most common; CAM may also refer to the use of a computer to assist in all operations of a manufacturing plant, including planning, management, transportation and storage. Its primary purpose is to create a faster production process and components and tooling with more precise dimensions and material consistency, which in some cases, uses only the required amount of raw material (thus minimizing waste), while simultaneously reducing energy consumption.

CAM is now a system used in schools and lower educational purposes. CAM is a subsequent computer-aided process after computer-aided design (CAD) and sometimes computer-aided engineering (CAE), as the model generated in CAD and verified in CAE can be input into CAM software, which then controls the machine tool [22].

Traditionally, CAM has been considered as a numerical control (NC) programming tool, wherein two-dimensional (2-D) or three-dimensional (3-D) models of components generated in CAD software are used to generate G-code to drive computer numerically controlled (CNC) machine tools. Simple designs such as bolt circles or basic contours do not necessitate importing a CAD file (Fig. 5).

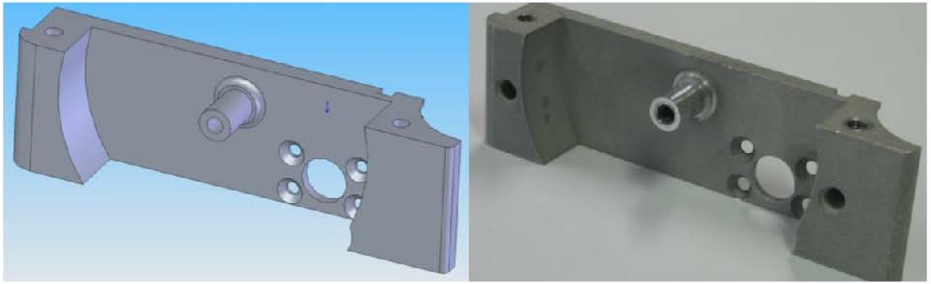


Fig. 5 CAD model and CNC machined part [22]

As with other "Computer-Aided" technologies, CAM does not eliminate the need for skilled professionals such as manufacturing engineers, NC programmers, or machinists. CAM, in fact, leverages both the value of the most skilled manufacturing professionals through advanced productivity tools, while building the skills of new professionals through visualization, simulation and optimization tools [22].

1.3. About FEM and FEA

In mathematics, the finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for differential equations. It uses variational methods (the calculus of variations) to minimize an error function and produce a stable solution. Analogous to the idea that connecting many tiny straight lines can approximate a larger circle, FEM encompasses all the methods for connecting many simple element equations over many small subdomains, named finite elements, to approximate a more complex equation over a larger domain [23].

1.3.1. A Brief History of the FEM and FEA

While it is difficult to quote a date of the invention of the finite element method, the method originated from the need to solve complex elasticity and structural analysis problems in civil and aeronautical engineering. Its development can be traced back to the work by A. Hrennikoff and R. Courant.

In China, in the later 1950's and early 1960's, based on the computations of dam constructions, K. Feng proposed a systematic numerical method for solving partial differential equations. The method was called the finite difference method based on variation principle, which was another independent invention of finite element method. Although the approaches used by these pioneers are different, they share one essential characteristic: mesh discretization of a continuous domain into a set of discrete sub-domains, usually called elements.

Hrennikoff's work discretizes the domain by using a lattice analogy, while Courant's approach divides the domain into finite triangular subregions to solve second order elliptic partial differential equations (PDEs) that arise from the problem of torsion of a cylinder. Courant's contribution was evolutionary, drawing on a large body of earlier results for PDEs developed by Rayleigh, Ritz, and Galerkin [23].

The finite element method obtained its real impetus in the 1960's and 70's by the developments of J.H. Argyris and co-workers at the University of Stuttgart, R.W. Clough and co-workers at UC Berkeley, O.C. Zienkiewicz [54] and co-workers at the University of Swansea, and Richard Gallagher [23] and co-workers at Cornell University. Further impetus was provided in these years by available open source finite element software programs. NASA sponsored the original version of NASTRAN, and UC Berkeley made the finite element program SAP IV widely available. A rigorous mathematical basis to the finite element method was provided in 1973 with the publication by Strang and Fix [23]. The method has since been generalized for the numerical modeling of physical systems in a wide variety of engineering disciplines, e.g., electromagnetism, heat transfer, and fluid dynamics; see O.C. Zienkiewicz, R.L.Taylor, and J.Z. Zhu [54] and K.J. Bathe [23].

Finite Element Analysis (FEA) was first developed in 1943 by R. Courant, who utilized the Ritz method of numerical analysis and minimization of variational calculus to obtain approximate solutions to vibration systems. Shortly thereafter, a paper published in 1956 by M. J. Turner, R. W. Clough, H. C. Martin, and L. J. Topp established a broader definition of numerical analysis. The paper centered on the "stiffness and deflection of complex structures".

By the early 70's, FEA was limited to expensive mainframe computers generally owned by the aeronautics, automotive, defense, and nuclear industries. Since the rapid decline in the cost of computers and the phenomenal increase in computing power, FEA has been developed to an incredible precision. Present day supercomputers are now able to produce accurate results for all kinds of parameters [28].

1.3.2. FEM in Engineering

1.3.2.1. Why Finite Element Method?

- ✓ Design analysis: hand calculations, experiments, and computer simulations
- ✓ FEM/FEA is the most widely applied computer simulation method in engineering
- ✓ Closely integrated with CAD/CAM applications.

1.3.2.2. What is Finite Element Analysis (FEA)? [45]

- ✓ A numerical method. FEA is a mathematical solution to engineering problems where a physical model is divided into discrete components. (Fig. 6);

- ✓ FEA models are defined by nodes and elements (commonly called a mesh);
- ✓ Traditionally, a branch of Solid Mechanics. Basic engineering equations, such as Hooke's law, are solved at the nodes and elements;
- ✓ A matrix equation with terms from each element is solved.
- ✓ Nowadays, a commonly used method for multiphysics problems;
- ✓ Predicts change within the element (e.g., deformation, stress);
- ✓ The results are plotted on the model by color to show the lowest and highest values;
- ✓ Provides a non-destructive means of testing products;
- ✓ Faster prototyping for "what if" scenarios;
- ✓ Design optimization;
- ✓ Speed up time to market by shortening the design cycle.

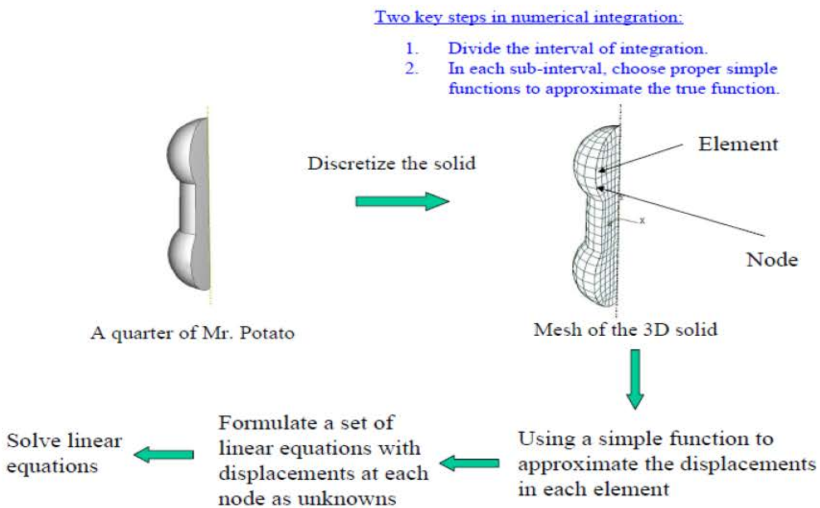


Fig. 6 How does FEA work? [45]

1.3.2.3. What areas can FEA be applied?

- ✓ Mechanical/Aerospace/Civil/Automobile Engineering (Fig. 7), (Fig. 8), Structure analysis: a cantilever, a bridge; solid mechanics: a gear, a automotive power train …
- ✓ Dynamics: vibration of Sears Tower, earthquake, bullet impact…
- ✓ Thermal / fluid flows analysis (Fig. 9): heat radiation of finned surface, thermal stress brake disc…
- ✓ Electromagnetics and electrical analysis: piezo actuator, electrical signal propagation…
- ✓ Geomechanics…
- ✓ Biomechanics (Fig. 10), biomaterials: human organs and tissues…

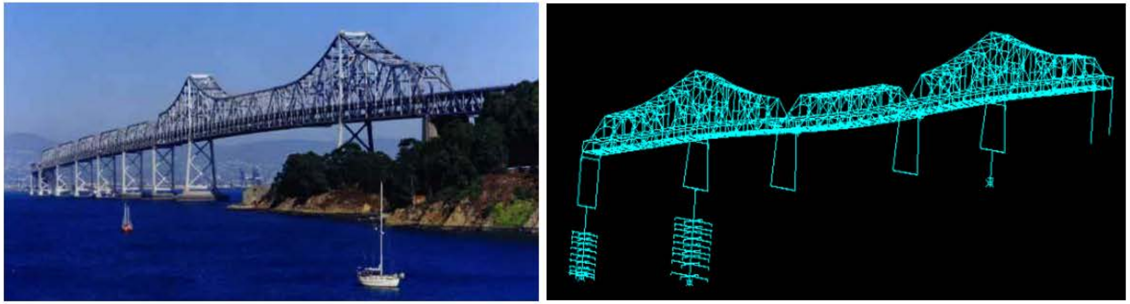


Fig. 7 FEA in civil engineering

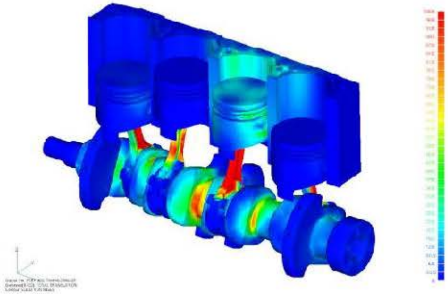


Fig. 8 FEA in automotive engineering

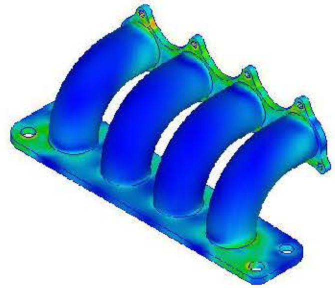


Fig. 9 FEA in thermal analysis

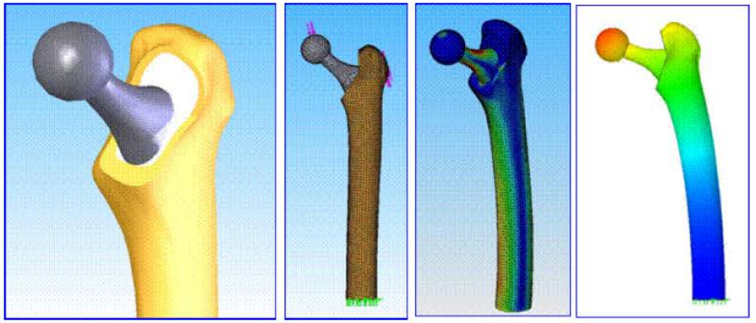
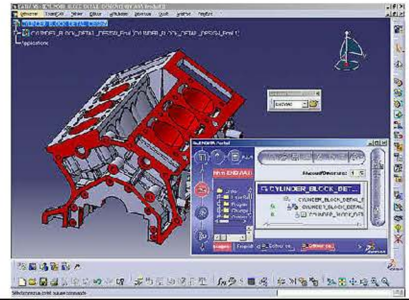
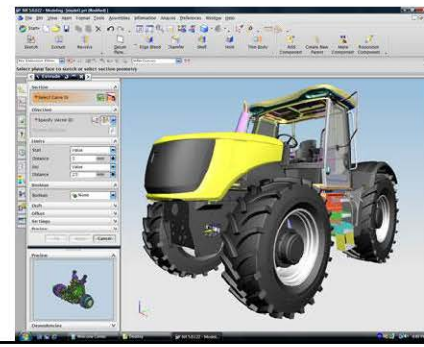


Fig. 10 FEA in biomechanics

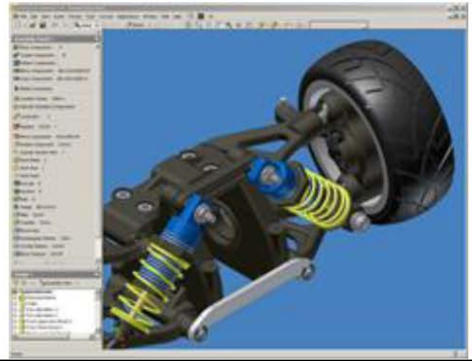
1.3.3. Available Commercial FEM Software Packages [18]

There are lot of companies providing softwares for CAD/CAM/CAE solutions worldwide. Each software is having its own importance and specialization. Some details of the widely used softwares is as below.

CATIA (CAD/CAE/CAM)	
CATIA (Computer Aided Three-dimensional Interactive Application) is a multi-platform CAD/CAM/CAE commercial software suite developed by the French company Dassault Systemes. Written in the C++ programming language, CATIA is the cornerstone of the Dassault Systemes product lifecycle management software suite. The software was created in the late 1970s and early 1980s to develop Dassault's Mirage fighter jet, then was adopted in the aerospace, automotive, shipbuilding, and other industries. www.3ds.com/products/catia/ welcome/	
SIEMENS NX (CAD/CAE/CAM)	
NX is the commercial CAD/CAM/CAE PLM software suite developed by Siemens PLM Software. NX is widely used in the engineering industry, especially in the automotive and aerospace sectors. NX has some presence in the consumer goods design sector. NX is a parametric solid / surface feature-based modeler. It uses the Parasolid geometric modeling kernel. Inventor (CAD/CAE).	

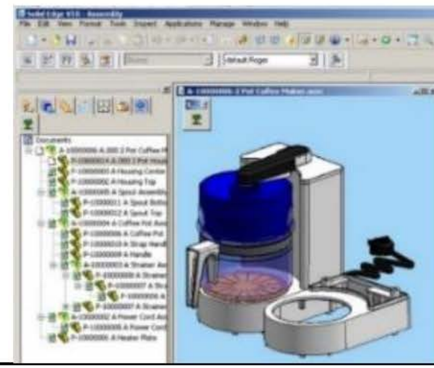
Inventor (CAD/CAE)

Autodesk Inventor is a CAD (Computer Aided Design or Computer Aided Drafting) software application for 3D mechanical design, product simulation, tooling creation, and design communication, developed and sold by Autodesk, Inc. Initially released in late 1999, Inventor filled a need for a CAD program specifically designed for easy of use, ease of learning, and communication of mechanical 3D design. In doing so, Inventor entered the CAD space primarily occupied by Solid Works. http://usa.autodesk.com/



Solid Edge (CAD/CAE)

Solid Edge is a 3D CAD parametric feature solid modeling software. It runs on Microsoft Windows and provides solid modeling, assembly modelling and drafting functionality for mechanical engineers. Through third party applications it has links to many other Product Lifecycle Management (PLM) technologies.

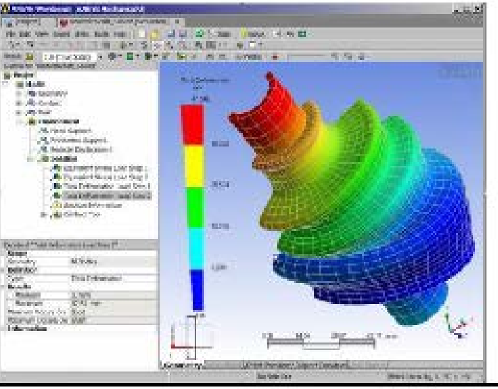


Solid Works (CAD/CAE)

SolidWorks is a 3D mechanical CAD (computer-aided design) program that runs on Microsoft Windows and was developed by Dassault Systèmes SolidWorks Corp., a subsidiary of Dassault Systèmes, S. A. (Vélizy, France). SolidWorks is currently used by over 3.4 million engineers and designers at more than 100,000 companies worldwide. http://www.solidworks.com/

ANSYS (CAE)

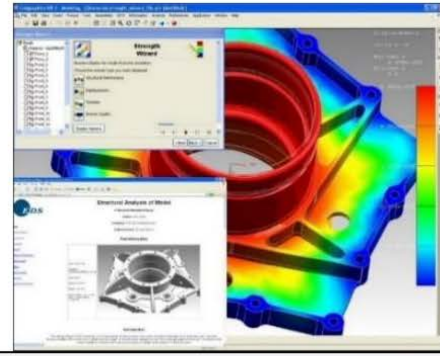
ANSYS, Inc. is an engineering simulation software provider founded by software engineer John Swanson. It develops general-purpose finite element analysis and computational fluid dynamics software. While ANSYS has developed a range of computer-aided engineering (CAE) products, it is perhaps best known for its ANSYS Mechanical and ANSYS Multiphysics products. ANSYS Mechanical and ANSYS Multiphysics software are non exportable analysis tools incorporating pre-processing (geometry creation, meshing), solver and post-processing modules in a graphical user interface. These are general-purpose finite element modeling packages for numerically solving mechanical problems, including static/dynamic structural analysis (both linear and non-linear), heat transfer and fluid problems, as well as acoustic and electro-magnetic problems. http://www.ansys.com/



NX Nastran (CAE/FEA)

NX Nastran is a Finite Element Analysis (FEA) and computer-aided engineering (CAE) tool provided by Siemens PLM Software.

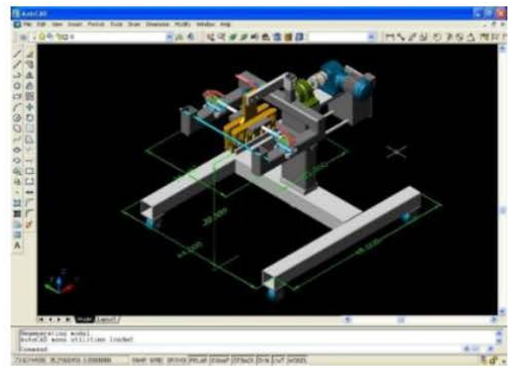
Since the 1970s, the original version of NASTRAN has been one of many FEA solutions of choice in many major industries including aerospace, defense, automotive, shipbuilding, heavy machinery, medical and consumer products. It is currently one of many computer-aided software solutions (ALGOR, ANSYS, ABAQUS and MARC to name a few others) for the analysis of stress, vibration, structural failure, structural durability, heat transfer, noise, acoustics, flutter and aeroelasticity. www.plm.automation.siemens.com/en_usproducts/nx/simulation/nastran/index.shtml



AutoCAD (CAD)

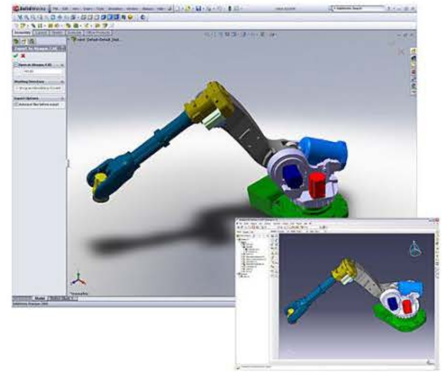
AutoCAD is a CAD (Computer Aided Design or Computer Aided Drafting) software application for 2D and 3D design and drafting, developed and sold by Autodesk, Inc. Initially released in late 1982, AutoCAD was one of the first CAD programs to run on personal computers, and notably the IBM PC. Most CAD software at the time ran on graphics terminals connected to mainframe computers or mini-computers.

In earlier releases, AutoCAD used primitive entities — such as lines, polylines, circles, arcs, and text — as the foundation for more complex objects. Since the mid-1990s, AutoCAD has supported custom objects through its C++ API. Modern AutoCAD includes a full set of basic solid modeling and 3D tools. With the release of AutoCAD 2007 came improved 3D modeling functionality, which meant better navigation when working in 3D. Moreover, it became easier to edit 3D models. The mental ray engine was included in rendering, it was now possible to do quality renderings. AutoCAD 2010 introduced parametric functionality and mesh modeling. http://usa.autodesk.com/



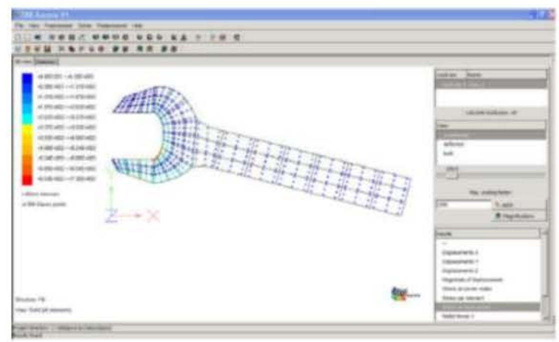
ABAQUS (CAE)

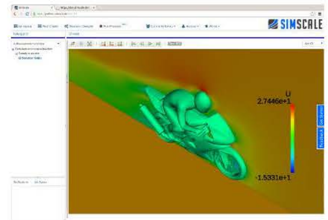
Abaqus is a commercial software package for finite element analysis developed by HKS Inc of Rhode Island, USA and now marketed under the SIMULIA brand of Dassault Systemes S.A. The Abaqus product suite consists of three core products: Abaqus/Standard, Abaqus/Explicit and Abaqus/CAE. Abaqus/Standard is a general-purpose solver using a traditional implicit integration scheme to solve finite element analyses. Abaqus/Explicit uses an explicit integration scheme to solve highly nonlinear transient dynamic and quasi-static analyses. Abaqus/CAE provides an integrated modelling (preprocessing) and visualization (postprocessing) environment for the analysis products. The Abaqus products use the open-source scripting language Python for scripting and customization. Abaqus/CAE uses the fox-toolkit for GUI development. http://www.simulia.com/



Z88 Aurora (FEA) [21]

Z88Aurora is a free finite element software package for static calculation in mechanical engineering and you can make large displacement analysis, stady state thermal analysis and natural frequency analysis. The FE-Solver, which calculates displacements, stresses and node forces has following features: 24 fe-elements (structure elements - trusses, beams and shafts, continuum elements - tetrahedrons and hexahedrons and some special elements, like shells, continuum shells, tori and plates, from linear to cubic approaches); a variety of boundary conditions (forces in all directions, displacemnets in all directions and pressure loads, positive and negative to the element face thermal loads); four numerical solvers; a iterative solver for large displacements; a solver for natural frequency analysis; calculation of stresses with three different criteria (maximum shear stress criterion - von Mises, maximum stress theory - Rankine and Tresca yield criterion). http://www.z88.de/



SimScale (FEA) [27]	
A new paradigm in engineering simulation. The SimScale platform provides access to powerful modeling and simulation technology via a standard web-browser. SimScale provides capacities for engineering simulation within various fields, such as structural mechanics, fluid dynamics, thermodynamics, acoustics, etc.	

1.4. Course Description

In this course the student learns to combine concepts in continuum mechanics, computer science and numerical analysis to solve problems using approximate solution techniques. Although several techniques are discussed, emphasis is placed on the finite element method.

The course consists of lecture material where the basic ideas are developed, problem sets that illustrate simple concepts, computer assignments using existing finite element programs that show typical results that can be obtained, and examinations that measure a student's mastery of the subject matter.

Finite Element Analysis (FEA) has become an integral part of design process in automotive, aviation, civil construction and various consumer and industrial goods industries.

Cut throat competition in the market puts tremendous pressure on the corporations to launch reasonably priced products in short time, making them to rely more on virtual tools (CAD/CAE) accelerate the design and development of products.

As dependability of the industries on virtual tools increases, so the responsibilities of the Finite Element Analysts to provide results with most accuracy within available resources and time constrains. FEA tools are being used to analyse multi disciplinary problems, including but not limited to structures, thermal and fluid flow, biotechnology, electromagnetism etc.

1.4.1. Course Overview

To date, the finite element method (FEM) is the most widely used numerical method for solving a variety of problems governed by partial differential equations in all areas of engineering. This course provides an introduction to the theory underlying the finite element method, with applications to problems drawn primarily from structural mechanics, but not exclusively.

There are two components to the course: the theoretical part will expose the principles (weak forms, Galerkin approximations, natural vs. essential boundary conditions, basis functions, error measures, etc) and the technical details (element types, integration rules, equation assembly, post-processing, etc). The second component aims at providing hands-on experience with the method through its application to simple problems (bars, beams, membranes, plates, flows, etc) of engineering interest, and to problems that merit the use of a computational tool. To this end, we will make use of CATIA™ and / or ANSYS™ (a commercial code) throughout the course.

The presentation of the material will be incremental starting from simple problems in order to illustrate and solidify the concepts, and progressing to complex problems. The emphasis will be on the basic principles, in the methodology, and in the physical interpretation of numerical results.

1.4.2. Course Objectives

This is an introductory course in the finite element method applied on the mechanical structures. At the end of the course, students will have to:

- understand the fundamental ideas of the FEM and FEA;
- understand the mathematical and physical principles underlying the Finite Element;
- demonstrate the ability to design a component using FEM analysis;
- make the student into a knowledgeable and critical numerical analyst;
- use the finite element method in solving various simple engineering problems;
- make the student aware of the importance of critically evaluating the results of approximate analyses in order to better assess their correctness;

- be able to analyze more complex problems (in solid mechanics or thermal analysis) using commercial FEM software such as ANSYS, CATIA;
- understand the importance of analysis and design, using the FEM, in the broader context of engineering practice;
- know the behavior and usage of each type of elements covered in this course;
- can interpret and evaluate the quality of the results (know the physics of the problems);
- be aware of the limitations of the FEM (don't misuse the FEM - a numerical tool).

1.4.3. Recommended Background

The course draws on material from mechanics, strength of materials, technical drawing, numerical analysis, and linear algebra. As such, the student should have a strong knowledge of fundamentals associated with these subjects. Although not emphasized as heavily as the above subjects, aspects of computer science also are presented in select lectures.