Chapter 1

Overview of Engineering Analysis
Chapter Objectives:

- To introduce the concept and principles of engineering analysis, and the vital roles that engineering analysis plays in professional engineering practices.

- To learn the need for the application of engineering analysis in three principal functions of professional engineering practices in: creation, problem solving and decision making.

- To illustrate the critical needs for engineers solving problems that relate to protection of properties and public safety, and also the needs for engineers making decisions in real-time situations that often involve grave consequences.

- To learn the roles that mathematics play in engineering analysis, and the ability to use mathematical modeling in problem solving and decision making in dealing with real physical situations.

- To present the needs for engineering analysis in mitigating or avoiding major catastrophes in engineering systems by selected case studies.
What is Engineering Analysis?

It is a **vital** TOOL for practicing engineering professionals in performing their duties in:

- **Creations**
- **Decision making**
- **Problem solving**
Engineers create:

“Scientists DISCOVER what it was, Engineers CREATE what it is not”

Engineers create “what it is not” in DESIGN to satisfy human needs:

Greatest Engineering Achievements of the 20th Century
as selected by the US Academy of Engineering

1. Electrification*
2. Automobile*
3. Airplane*
4. Water supply and distribution
5. Electronics
6. Radio and television
7. Agriculture mechanization*
8. Computers
9. Telephone
10. Air conditioning and refrigeration*
11. Highways
12. Spacecraft*
13. Internet
14. Imaging
15. Household appliances*
16. Health technologies
17. Petroleum and petrochemical technologies
18. Laser and fiber optics
19. Nuclear technology*
20. High performance materials

* With significant mechanical engineering involvements
Engineers make **DECISIONS** – at all times, and often crucial ones:

**Decisions are required in:**

- **Design** – Configurations
  - Selection of design methodology, materials and fabrication methods
  - Assembly, packaging and shipping

- **Manufacturing** – Tools and machine tools
  - Fabrication processes
  - Quality control and assurance

- **Maintenance** – Routine inspections and Procedures

- **Unexpected cases with potential grave consequences** –
  - Change of customer requirements
  - Malfunctioning of machines and equipment
  - Defects in products

**Critical Decisions by Engineers** on what to do if **flaws** or **cracks** appear on the surfaces of:

- **Pressurized pipelines**
- or
- **A jumbo jet airplane?**
Engineers solve **Problems** – often in ways like fire-fighting:

**Problems relating to:**

- Design fault and ambiguity
- Manufacturing disorder
- Malfunction of equipment
- Inferior quality in production
- Run-away cost control
- Resolving customer complaints and grievances
- Public grievances and mistrust
All **TASKS** relating to:

- Creation
- Decision making
- Problems solving

are of **PHYSICAL nature**

The required **ANSWERS**
are of **PHYSICAL nature** too
Translate engineering problems into math form by:
1) Idealizing physical situations.
2) Identifying idealized physical situation with available math representations
3) Formulate math models, e.g., expressions, equations.

Conclusion: Math plays a principal role as a servant to Engineering (the Master) in engineering practices.
Mathematical Modeling

Math modeling is a practice involving the translation of physical (engineering) situations into mathematical forms.

Tool Box for Engineering Analysis:

- Empirical formulas
- Algebraic equations and formulas from textbooks and handbooks
- Differential and integral equations with appropriate conditions fit to the specific problems
- Numerical solutions, e.g., by finite element method (FEM) or finite difference method (FDM).

Many mathematical formulas and expressions are available in handbooks, e.g.:

Example of Engineering Analysis by **Empirical Formula**

**Estimate pressure drop in fluid flow in pipes:**

Fluids flow in pipeline requires **pressure** supplied either by pumps, fans or gravitation. Pressure drop $\Delta P$ is the basis for selecting a powerful enough pump for the intended fluid flow in a pipeline. Unfortunately, it is too complicated to be computed. But engineers must have this information to design the pipe flow. Following empirical formula is often used:

$$ P_1 - P_2 = \Delta P = f \frac{\rho v^2 L}{2D} $$

where $\rho$ = mass density of the fluid, $v$ = average velocity of the fluid flow, $L$ = length of the pipe, $D$ = diameter of the pipe, and $f$ = friction factor from Moody chart.

The friction factor $f$ with the values available from the Moody chart is derived from experiments.

$$ \Delta P = f \frac{\rho v^2}{2} \frac{\pi R_b}{D} \frac{\theta}{180^\circ} + \frac{1}{2} k_b \rho v^2 $$

where $f$ = Moody friction factor, $v$ = average velocity of fluid flow,

$D$ = diameter of the pipe, $R_b$ = radius of the pipe bend, and

$k_b$ = the bend loss coefficient.

Numerical values of the bend loss coefficient $k_b$ are available in a handbook:

The estimated pressure drop $\Delta P$ is then used to design the pump or fan to drive the fluid through a pipeline.
Examples of Using Algebraic equations and formulas from textbooks and handbooks in Engineering Analysis

1) Determine the dynamic force induced by changing velocity of moving solid using the Newton’s Law:

Induced force \( F \) = Mass of the moving solid \( M \) x Acceleration \( a \) or Deceleration \( -a \)

2) Determine the induced stress to a solid bar by applied force using the Hooke’s Law:

Induced stress \( \sigma = F/A \) = \( E \) x Induced strain \( \epsilon = \Delta L/L \)

where \( F \) = applied force, \( A \) = cross-sectional area, \( E \) = Young’s modulus (material property)
\( \Delta L \) = elongation or contraction of the bar, \( L \) = original length of the bar

3) Determine the velocity of fluid flow in a pipe (nozzle) with variable cross-sections using continuity law:

\[ V_2 = \frac{A_1}{A_2} V_1 \]
Examples of using **Differential and Integral Equations** in Engineering Analysis

1) Differential Equations in Engineering Analysis:

Determine the rate of solvent A with lighter concentration diffuses into solvent B with heavier concentration:

\[
\frac{\partial C(x, t)}{\partial t} = D \frac{\partial^2 C(x, t)}{\partial x^2}
\]

where \( C(x, t) \) = concentration of A at depth \( x \) and time \( t \), \( D \) = diffusivity of diffusion of A to B

2) Integral Equation in Engineering Analysis:

Solve for function \( f(x) \) in the equation:

\[
\int_{0}^{1} f(x) \cos ax \, dx = \begin{cases} 
1 & \text{if } 0 \leq a \leq 1 \\
0 & \text{if } a > 1 
\end{cases}
\]

Solution:

\[
f(x) = \frac{2(1 - \cos x)}{\pi x^2}
\]
Numerical Solutions for Engineering Analysis

Numerical solution methods are techniques by which the mathematical problems that are associated with engineering analysis cannot be solved by analytical methods, such as by the above methods in the “tool box.”

Numerical techniques have greatly expanded the types of problems that engineers can handle in: (1) Solving nonlinear polynomial equations, (2) Graphic expressions of functions, (3) differential equations by “finite difference methods” and (4) Problems with complicated geometry, loading and boundary conditions, such as by the “finite element methods.”

Example: To determine the stress induced in the plate with the following loading condition:

Plain solid plate: EASY

Plate with a small hole of diameter d is a much, much harder case

Numerical solution by Finite element method:

Principal tasks in numerical methods for engineering analysis is to develop algorithms that involve arithmetic and logical operations so that digital computers can perform such operations.
The Four Stages in General Engineering Analysis

Engineers are expected to perform “Engineering analysis” on a variety of different cases in their careers. There is no set rules or procedure to follow for such analyses.

Below are the 4 stages that one may follow in his (her) engineering analysis.

**Stage 1: Identification of the physical problem** – specification of the problem:
To ensure knowing what the analysis is for on:
- Intended application(s)
- Possible geometry and size (dimensions)
- Materials for all components
- Loading: range in normal and overloading; nature of loading
- Other constraints and conditions, e.g., space, cost, government regulations

**Stage 2: Idealization of actual physical situations for subsequent mathematical analysis:**
Often, the engineer needs to make assumptions and hypotheses on the physical conditions of the problem, so that he (she) can handle the analysis by his (her) capability with the “tools” available to him or her.

**Stage 3: Mathematical modeling and analysis:** by whatever means he (she) believes applicable, e.g., solution methods from handbooks, computer software, company handbooks or own derived formula and equations, including differential equations, etc.

**Stage 4: Interpretation of results** – a tricky but important task.
To translate the results of math modeling with numbers, charts, graphs to physical sense applicable to the problem on hands
Example on a Simple Engineering Analysis Involving the Four Stages in General Engineering Analysis

Stage 1: The problem:
To design a coat hanger that will have sufficient strength to hang up to 6 pounds for an overcoat.
A design synthesis resulted in the following conditions:
- Geometry and dimensions as shown:
  - Material: plastic with allowable tensile strength @ 500 psi from a materials handbook

Stage 2: Idealization of actual physical situations for subsequent mathematical modeling and analysis:
This is a “beam bending” problem. The solution on the strength of the hanger appears available in “mechanics of materials.” But the required geometry shown above is too complicated to be handled by available formula in textbooks or design handbooks. Need to make the following idealizations in order to use available formula in the analysis

- On geometry:
- On loading condition:
  - \( P \) – uniform distributed load of the coat = 0.3243 lb/in
- On boundary (end) conditions: Rigidly held ends (how realistic is this?)
**Stage 3:** Mathematical modeling and analysis:
Derive or search for suitable mathematical formulations to obtain solution on the specific engineering problem.

- In this case of coat hanger design, the solution required is:

  “Will the assumed geometry and size of the hanger withstand the specified maximum weight of the coat up to 6 lbs?” – *a physical statement*

- The *required solution* is to keep the **maximum stress** in coat hanger induced by the expected **maximum load** (the weight of the coat) **BELOW** the allowable limit (the **maximum tensile strength**) of the hanger material (500 psi), as given (another physical statement)

- With the “idealization” in Stage 2, the maximum stress in the hanger can be computed from the formula on “**simple beam theory**” available from “mechanics of materials” (e.g., CE 112) textbook or a handbook for mechanical engineers

\[
\sigma_m = \frac{M_m C}{I}
\]

where \(M_m\) = max. bending moment, \(C\) radius of frame rod, \(I\) = area moment of Inertia of the frame rod

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**Case of coat hanger**

Distributed load, \(P\)

Maximum stress, \(\sigma_m = \frac{M_m C}{I}\)

\(23.23^\circ\)

\(9.25''\)

**Available case in textbook**

Distributed load, \(PCos(23.23^\circ) = 0.298\) lb/in
Results of Stage 3 analysis:

We may compute the following:

The area moment of inertia of the frame rod, \( I = \frac{\pi d^4}{64} = 1.9165 \times 10^{-4} \text{ in}^4 \)

The maximum bending moment, \( M_m = \frac{p\ell^2}{8} = \frac{0.298x(9.25)^2}{8} = 3.1872 \text{ lb-in} \)

The radius of the frame rod, \( C = 0.125" \)

The maximum bending stress, \( \sigma_m = \frac{3.1872 \times 0.125}{1.9165 \times 10^{-4}} = 2078.8 \text{ psi} \)

occurs at both ends of the frame rod
Stage 4: Interpretation of results – a tricky but very important task:

- Result from analysis in Stage 3 normally is in the form of NUMBERS, such as $\sigma_m = 2078.8$ psi as in the present case of a coat hanger design.
- Require ways to interpret these numbers into physical senses, e.g. in the current case: “Can the coat hanger with the assumed geometry and dimensions carry a 6-lb coat?”

- There are VARIOUS ways available for such translation:

  A) For the case of structure-related design ONLY, one would use the following criterion:

  **The max. stress, $\sigma_m < \sigma_a$**

  where $\sigma_a = \text{allowable stress} = \text{Maximum tensile strength from handbooks/Safety Factor (SF)}$

- The SF in an analysis relates to “the extent engineers can make use of the strength of the material”
- There are a number of factors determining the SF in a structure design;
- The value of SF is set by designers based on the degree of sophistication of the analysis – the less “idealization” made in Stage 2: e.g., low value of SF for more sophisticated analyses with fewer idealization and assumptions made in the analysis. Physically it means less material is needed
- The value of SF also relates to possible potential consequence of the case in the analysis

For the case of coat hanger design, the $\sigma_m = 2078$ psi > $\sigma_a = 500$ psi with SF = 1. Physically, it means the coat hanger with the set geometry and dimensions **CANNOT** carry a 6-pound coat. The engineer will either adjust the assumed dimensions of the hanger, or reduce the weight of garment for the hanger to carry, following the following general design procedure.
**B) Stage 4 Interpretation of Results in **GENERAL** – General procedure in engineering design**

Stage 1: Understand the physical problem

Stage 2: Idealization for math modeling

Stage 3: Math modeling & analysis

Stage 4: Interpretation of results

No safety factors are involved
Chapter-End Assignment

1. Read the Example on Application of Engineering Analysis on a bridge on P. 9.

2. Conduct an engineering analysis on the above example but include the weights of the steel structure and the required concrete road surface for the bridge. Remind you that you do not always have the information and conditions given in your design analyses. You, as an engineer, needs to make reasonable and logical assumptions on these missing information based on available reference “tools” available to you.

3. Be prepared to answer the question on the significance of “Safety Factor” used in a design analysis of a structure or machine component. What are the fundamental principles for determining the numerical value of this factor? Explain why a SF = 4 is used in pressure vessel design by ASME design code, yet SF = 1.2 is used in aircraft structure design.

4. Be prepared to offer example of engineers making decisions and solve problems based on your personal experience.