

MODELING AND USE OF FEM ON STATIC STRUCTURE

A SECOND YEAR PROJECT REPORT

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF B.Sc. IN COMPUTATIONAL MATHEMATICS

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CERTIFICATION

This project entitled "Modeling and use of FEM on static structure" is carried out under my supervision for the specified entire period satisfactorily, and is hereby certified as a work done by following students

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APPROVED BY:

I hereby declare that the candidate qualifies to submit this report of the Math Project (MATH-252) to the Department of Mathematics.

Head of the Department

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Date: April 17, 2022

CONTENTS

CERTIFICATION	ii
LIST OF FIGURES	iv
LIST OF TABLES	v
LIST OF SYMBOLS	vi
1 MOTIVATION/INTRODUCTION	1
1.1 Context/Rationale/Background	1
1.2 Objectives	1
1.3 Significance/Scope	1
1.4 Limitations	2
2 METHODOLOGY/MODEL EQUATION	3
2.1 Theoretical/Conceptual Framework	3
3 RESULTS AND DISCUSSIONS	9
3.1 Result1	9
4 CONCLUSIONS	10

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

Your parameters here.

CHAPTER 1

MOTIVATION/INTRODUCTION

1.1 Context/Rationale/Background

In this section, the author(s) shall discuss the historical background related to the work along with the introduction of the topic in brief.

1.2 Objectives

1. To set up differential equations with variable boundary conditions.
2. To learn to perform numericals manually and then implement those in a high level programming language
3. To learn about FEM, its variations, and its application to various mechanical problems.
4. Visualization and Project Writing.

1.3 Significance/Scope

The use of numerical methods is prevalent in all fields of science and technology today. Our project focuses on one powerful numerical tool known as FEM which is theoretically sound and computationally efficient. The basic ideas of such tools which one is sure to encounter later will be very beneficial. This project also opens up the world of variational calculus and its applications which are generally not covered in undergraduate mathematics.

The computer implementation of a package that implements the algorithm for solving problem using FEM while handling inputs and visualizing the output is a stark contrast from the dummy math problem that are usually used in computer programming classes to teach concepts of general programming rather than mathematical programming. This project imparts the skill to convert mathematical knowledge into efficient and all around packages that solve problems that are based on real world applications and are similar to ones encountered later at work in industries or academia.

1.4 Limitations

The project only focuses on application of FEM to a single differential equation and thus despite being a great starting point for diving into the world of finite element method, it lacks behind in providing full demonstration of its potential. We have applied FEM to solve 2D truss structures. The computer implementation is also limited to this subset of problems and can work with only 2D trusses.

CHAPTER 2

METHODOLOGY/MODEL

EQUATION

2.1 Theoretical/Conceptual Framework

In this section, the author(s) should describe the theoretical/mathematical principles behind the whole work relative to the project. The information collected from literature review shall be relevant in this section.

Consider

$$-\frac{d}{dx} \left[a(x) \frac{du}{dx} \right] = f(x) \quad \text{for} \quad 0 < x < L. \quad (2.1)$$

$$(2.2)$$

for $u(x)$ subject to the boundary conditions

$$u(0) = u_0 \quad (2.3)$$

$$a(x) \frac{du}{dx} \Big|_{x=L} = Q_L \quad (2.4)$$

where $a(x)$ and $f(x)$ are known functions and u_0 and Q_L are known values. In case of bar (which is a axially loaded structure)

u = displacement

$a(x) = EA$ (stiffness)

f = distributed axial force

Q_L = axial load

Now, we want an approximation of $u(x)$ in the form

$$u(x) \approx u_N(x) = \sum_{j=1}^N c_j \phi_j(x) + \phi_0(x) \quad (2.5)$$

Substituting $U_N(x)$ in our Differential Equation,

$$-\frac{d}{dx} \left[a(x) \frac{dU_N}{dx} \right] = f(x) \quad \text{for} \quad 0 < x < L. \quad (2.6)$$

If this equally holds for all $x \in [0, L]$ the solution is exact. Since, we assume it only as an approximation. we define Residual Function $R(x, c_1, c_2, c_3, \dots, c_N)$ as

$$R = -\frac{d}{dx} \left[a(x) \frac{dU_N}{dx} \right] - f(x) \quad (2.7)$$

We have $R \neq 0 \forall x \in [0, L]$ as a U_N is only a approximation to solution.

Now we have various ways to minimize R in some senses over the domain to make this approximation close to the actual solution

1. Collocation Method

It forces that R is zero at selected N points of the domain.

i.e;

$$R(x, c_1, c_2, c_3, \dots, c_N) = 0 \quad \forall x = x_i, i = 1, 2, \dots, N \quad (2.8)$$

2. Least Square Method

$$\frac{\partial}{\partial c_j} \int_0^L R^2 dx = 0 \quad \forall i = 1, 2, \dots, N \quad (2.9)$$

3. Weighted Residual Method we desire that

$$\int_0^L w_i(x) R dx = 0 \quad \forall i = 1, 2, \dots, N \quad (2.10)$$

where $w_i(x)$ are N linearly independent functions called weight functions.

Now we convert our differential equation and boundary condition to weak form.

- Step 1 :

We write the weighted integral statement, i.e;

$$\int_0^L w \left[-\frac{d}{dx} \left(a(x) \frac{du}{dx} \right) - f \right] dx = 0 \quad (2.11)$$

It is equivalent to differential equations and does not include any boundary conditions and thus the variable u must be differentiable to as many order as is required by the differential equation.

- Step 2

Weakening Differentiability conditions

$$\int_0^L \left(w \left[-\frac{d}{dx} \left(a(x) \frac{du}{dx} \right) \right] - wf \right) dx = 0 \quad (2.12)$$

Integrating by parts, we get,

$$\int_0^L \left[a \frac{dw}{dx} \frac{du}{dx} - wf \right] dx - \left[wa \frac{du}{dx} \right]_0^L = 0 \quad (2.13)$$

we have used the fact that

$$\int_a^b \left(w \frac{dv}{dx} \right) dx = - \int_a^b v dw + [wv]_0^L = 0 \quad (2.14)$$

by considering,

$$v = -a \frac{du}{dx} \quad (2.15)$$

we can see that now we require that w be differentiable at least once but this also made that u needs to be differentiable only once even though the equation is of second order.// Now, we take care of the boundary conditions which are of two types

- Natural Boundary condition
- Essential Boundary Condition

Before defining these conditions we define primary and secondary variables.

Definition 1 *Primary Variable pass*

Definition 2 *Secondary Variable pass*

In our case , $a \frac{du}{dx}$ is secondary variable.

If secondary variable(SV) is specified in the boundary, then such conditions are called natural boundary conditions (NBC). If primary variable(PV) is specified in the boundary, then such conditions are called essential boundary conditions (NBC).

let us now define secondary variable as Q.

$$Q = a \frac{du}{dx} n_x \quad (2.16)$$

where n_x is ???

For 1D problems,

$$n_x = -1 \quad \text{at left} \quad (2.17)$$

$$n_x = 1 \quad \text{at right} \quad (2.18)$$

$$\int_0^L \left[a \frac{dw}{dx} \frac{du}{dx} - wf \right] dx - \left[wa \frac{du}{dx} \right]_0^L = 0 \quad (2.19)$$

\Rightarrow

$$\int_0^L \left[a \frac{dw}{dx} \frac{du}{dx} - wf \right] dx + wa \frac{du}{dx} \Big|_{x=L} - wa \frac{du}{dx} \Big|_{x=0} = 0 \quad (2.20)$$

since $n_x = -1$ at $x = 0$ and $n_x = 1$ at $x = L$

$$\int_0^L \left[a \frac{dw}{dx} \frac{du}{dx} - wf \right] dx - n_x wa \frac{du}{dx} \Big|_{x=L} - n_x wa \frac{du}{dx} \Big|_{x=0} = 0 \quad (2.21)$$

$$\int_0^L \left[a \frac{dw}{dx} \frac{du}{dx} - wf \right] dx - (wQ)_0 - (wQ)_L = 0 \quad (2.22)$$

Finally we require that weight functions vanishes at boundaries where essential boundary conditions are specified.

$$u(0) = u_0 \implies w(0) = 0 \quad (2.23)$$

Thus, we get

$$\int_0^L \left[a \frac{dw}{dx} \frac{du}{dx} - wf \right] dx - w(L)Q_L = 0 \quad (2.24)$$

$$B(w, u) = \int_0^L a \frac{dw}{dx} \frac{du}{dx} dx \quad (2.25)$$

$$l(w) = \int_0^L wf dx + w(L)Q_L \quad (2.26)$$

Hence, our weak form can be written as

$$0 = B(w, u) - l(w) \quad (2.27)$$

or ,

$$B(w, u) = l(w) \quad (2.28)$$

This is the variational form of the problem that is associated with our ODE and its boundary conditions.

When the differential equation is linear and of even order, the resulting weak form will have symmetric bi-linear form in u and w.

Let us now choose the approximate solutions that satisfy the two conditions for primary variables as other conditions are already included in the weak form. i.e,

$$u_h^e(x_a) = u_1^e \quad (2.29)$$

$$u_h^e(x_b) = u_2^e \quad (2.30)$$

let,

$$u_h^e(x) = c_1 + c_2x \quad (2.31)$$

Then by the conditions,

$$u_h^e(x_a) = c_1 + c_2 x_a = u_1^e \quad (2.32)$$

$$u_h^e(x_b) = c_1 + c_2 x_b = u_2^e \quad (2.33)$$

writing in matrix form, we obtain

$$\begin{bmatrix} u_1^e \\ u_2^e \end{bmatrix} = \begin{bmatrix} 1 & x_a \\ 1 & x_b \end{bmatrix} \begin{bmatrix} c_1^e \\ c_2^e \end{bmatrix} \quad (2.34)$$

We can rewrite the equations as

$$\begin{bmatrix} c_1^e \\ c_2^e \end{bmatrix} = \frac{1}{x_b - x_a} \begin{bmatrix} x_b & -x_a \\ -1 & 1 \end{bmatrix} \begin{bmatrix} u_1^e \\ u_2^e \end{bmatrix} \quad (2.35)$$

Hence we get,

$$c_1^e = \frac{1}{h_e} (x_b u_1^e - x_a u_2^e) \quad (2.36)$$

$$c_2^e = \frac{1}{h_e} (-u_1^e + u_2^e) \quad (2.37)$$

If we let,

$$\alpha_1^e = x_b$$

$$\alpha_2^e = -x_a$$

$$\beta_1^e = -1$$

$$\beta_2^e = 1$$

$$c_1^e = \frac{1}{h_e} (\alpha_1^e u_1^e + \alpha_2^e u_2^e) \quad (2.38)$$

$$c_2^e = \frac{1}{h_e} (\beta_1^e u_1^e + \beta_2^e u_2^e) \quad (2.39)$$

Hence,

$$U_h^e(x) = \frac{1}{h_e} [\alpha_1^e u_1^e + \alpha_2^e u_2^e + (\beta_1^e u_1^e + \beta_2^e u_2^e)x]$$

$$U_h^e(x) = \frac{1}{h_e} [\alpha_1^e + \beta_1^e x] u_1^e + \frac{1}{h_e} [\alpha_2^e + \beta_2^e x] u_2^e$$

$$U_h^e(x) = \sum_{j=1}^2 \frac{1}{h_e} [\alpha_j^e + \beta_j^e x] u_j^e \quad (2.40)$$

$$U_h^e(x) = \sum_{j=1}^2 \psi_j^e(x) u_j^e \quad (2.41)$$

where $\psi_j^e(x)$ are known as interpolation functions.

CHAPTER 3

RESULTS AND DISCUSSIONS

3.1 Result1

In this chapter, the author(s) shall present the results and simulations (in the form of numerical data or graphical form) of the theory described in CHAPTER-2 and finally discuss the results.

CHAPTER 4

CONCLUSIONS

In this section, the author(s) shall summarize the main points and the results of the work. Include key facts from the background research to help explain your results as needed.

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- [1] R. Doe, *Miktex url*, <http://www.miktex.org>, June 2009.
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