

Determination of Resultant Forces for 2D Hyperstatic Frames using Android-Based Frame Design Application and Finite Element Analysis

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Abstract— The slope deflection method assumes all joints are considered rigid, which means the angle does not change under any loads. This ensures that compatibility and deflection are neglected due to shear and axial stress. The numerical determination of forces and deformation in structures through applying the slope deflection method necessitates a relatively extended computational time and demands high-precision results. An effective tool can efficiently and precisely determine internal forces and structural deformations. This study utilizes the Frame Design Application version 5177, initially released on 24 June 2012 and has since been updated as of 2 February 2022, an Android-based application. Utilizing the Frame Design Application facilitates the expeditious and precise determination of internal forces and structural deformations. It is a valuable tool for professionals in civil engineering, mechanical engineering, and architecture, as well as students seeking to build 2D hyperstatic frames through Finite Element Analysis (FEA). The primary objective of this paper is to evaluate the precision of the Frame Design Application to determine its suitability for educational purposes. This paper will also evaluate the precision of the analysis outcomes by manual calculations and the utilization of SAP2000 Software. The provided analysis results exhibit negligible disparities. The Frame Design Application is a highly recommended tool for those in civil engineering, mechanical engineering, architecture and students seeking to design 2D hyperstatic frames through FEA.

Keywords: *Android, Frame design, Finite element analysis, Hyperstatic frame, SAP 2000.*

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1. Introduction

Basically, engineering mechanics literature mainly focuses on the slope deflection method of beams that possess uniform effective stiffness throughout their whole length [1], [2]. Hence, using equations becomes imperative in resolving the challenges posed by statically indeterminate constructions featuring distinct effective stiffnesses (EI) inside a single beam [3]. The derivation of this equation has a considerable level of difficulty due to the necessity of initially deriving the angular rotation and fixed end moments for various circumstances of EI stiffness. The calculation is iteratively performed for various stress and stiffness conditions within a single beam. The reaction and internal force value can be obtained from the findings derived and utilized from this equation. The slope deflection method analyzes the indeterminate structure containing beams and frames [4]-[8]. This method depends mainly on the displacement, which is rotation at joints, and the relative displacements between the ends of elements. The method used to calculate the end moments at each element depends on the moment produced from displacement and from applied loads used by calculating the fixed end moments [9-11]. The method assumes all joints are considered rigid (which means the angle does not

change under loads) [12], [13]. This ensures that compatibility and deflection are neglected due to shear and axial stress [14]. Figure 1 displays the sign convention: 1) Moments and rotation clockwise positive; 2) Relative displacement downward positive [15-17]. Consider the beam in a figure that carries and deforms under these loads, as shown in Figure 2. Calculate the fixed end moments based on Figure 3.

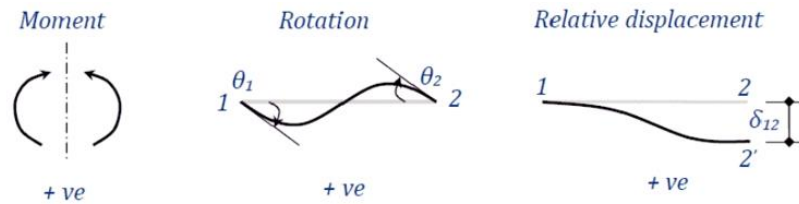


Figure 1. Sign convention

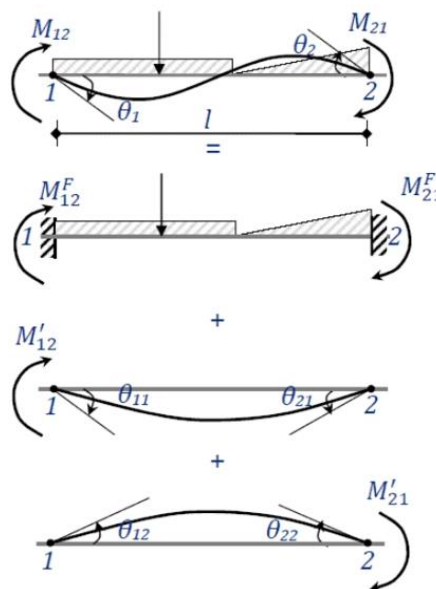


Figure 2. Deforms under these loads

Where:

M_{12}^f is the fixed end moment at joint 1.

M_{21}^f is the fixed end moment at joint 2.

M_{12}' is the moment applied at 1 to produce rotations θ_{11} & θ_{21} .

M_{21}' is the moment applied at 2 to produce rotations θ_{12} & θ_{22} .

The numerical determination of forces and deformation in structures through applying the slope deflection method necessitates a relatively extended computational time and demands high precision. In the contemporary period characterized by rapid technological advancements, various Software and applications have been readily accessible, facilitating convenient installation processes [18]. An effective tool for efficiently and precisely determining internal forces and structural deformations is the Frame Design Application version 5177, initially released on 24 June 2012 and has since been updated as of 2 February 2022. The Frame Design Application is an Android-based application [19] that can be downloaded for free from the Google Play Store. Utilizing the Frame Design Application facilitates the expeditious and precise determination of internal forces and structural deformations. The Frame Design Application employs the Finite Element Method (FEM). It is a valuable tool for professionals in civil engineering, mechanical engineering, and architecture, as well as students

seeking to build 2D hyperstatic frames through Finite Element Analysis (FEA). The primary interface of the Frame Design Application, as depicted in Figure 4, is showcased on the Play Store. The primary objective of this paper is to evaluate the precision of the Frame Design Application to determine its suitability for educational purposes. This paper will also evaluate the precision of the analysis outcomes by manual calculations [20-22] and the utilization of SAP2000 Software [23-25].

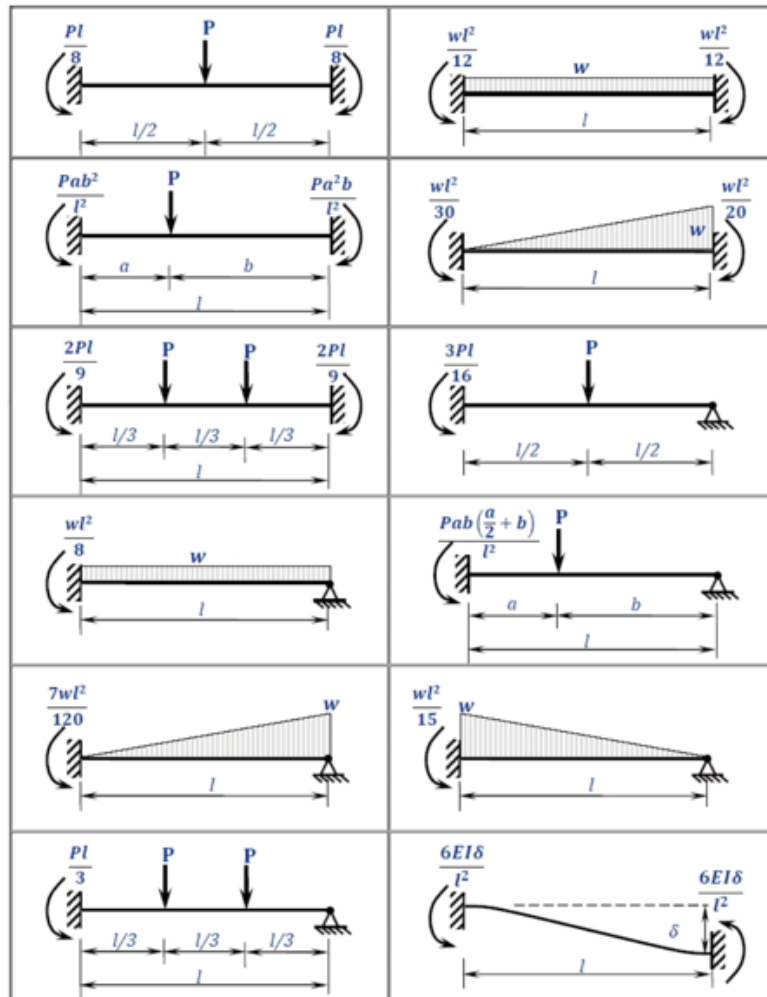


Figure 3. Calculate the fixed end moments [22]

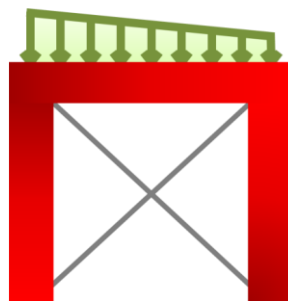


Figure 4. The primary interface of the Frame Design Application

2. Method

This paper presents a modeling and analysis of a 2-dimensional frame construction, as depicted in Figure 5, utilizing the Frame Design Application. The flow diagram in Figure 6 illustrates the sequential processes involved in the modeling and analysis process using the Frame Design Application.

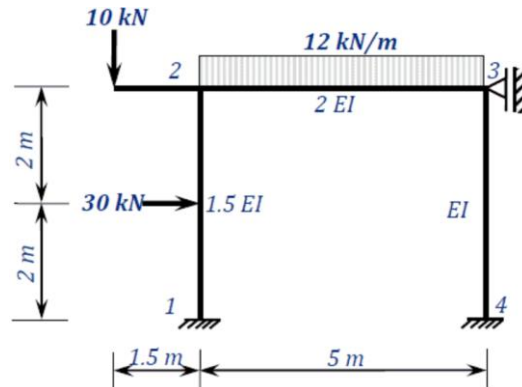


Figure 5. Case study of 2D hyperstatic frame

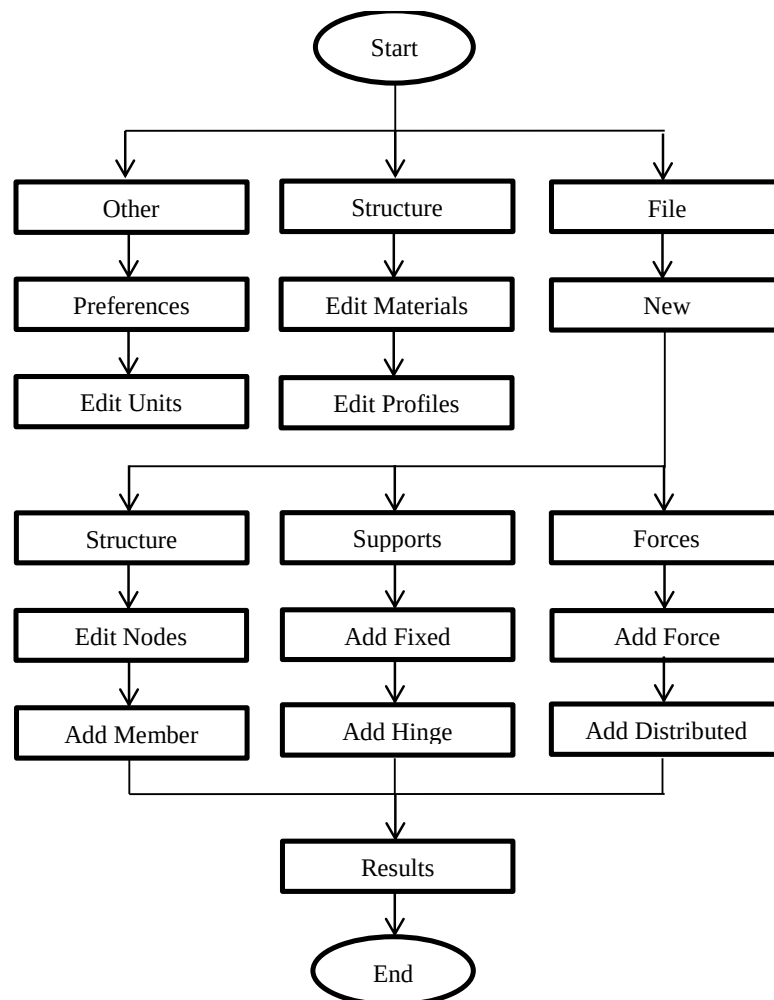


Figure 6. Flowchart for the frame analysis

3. Result and Discussion

3.1 Frame Design using Android-Based Application

The geometric representation of the outcomes obtained from the analysis of a 2-dimensional frame structure can be observed in Figure 7. Additionally, the acquired analysis findings are shown in diagrammatic form in Figure 8 for axial force, Figure 9 for bending moment, and Figure 10 for shear force.

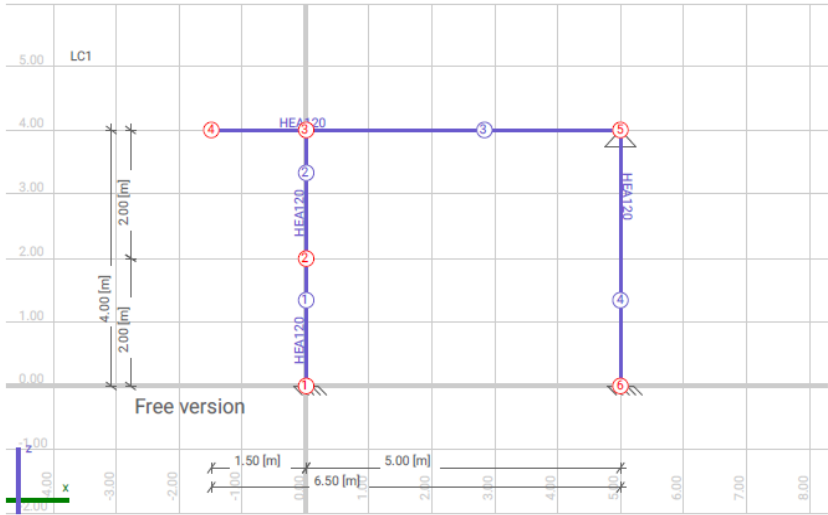


Figure 7. Geometry of frame

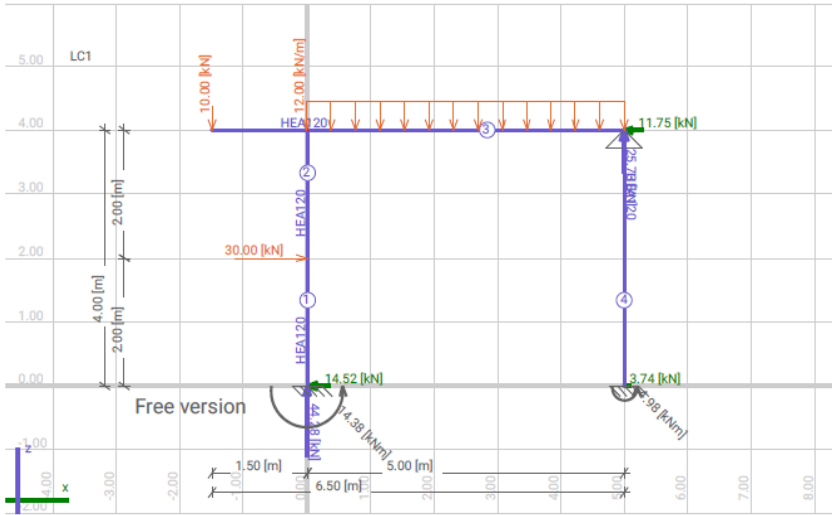


Figure 8. Axial force

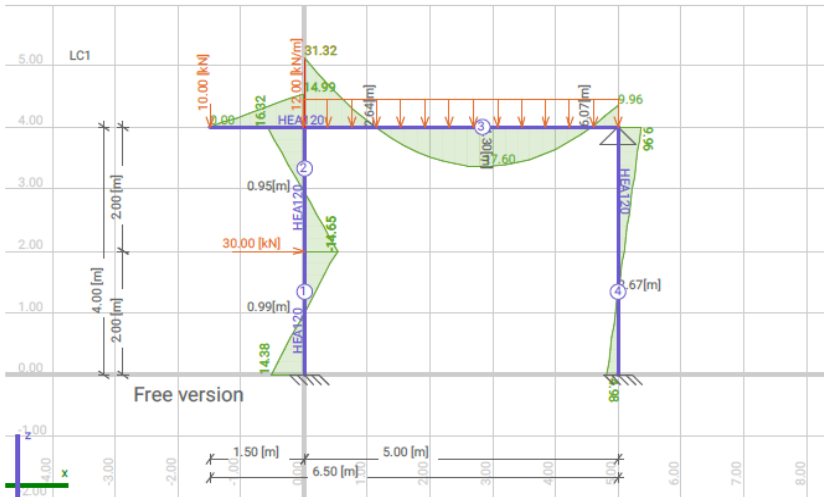


Figure 9. Bending moment diagram

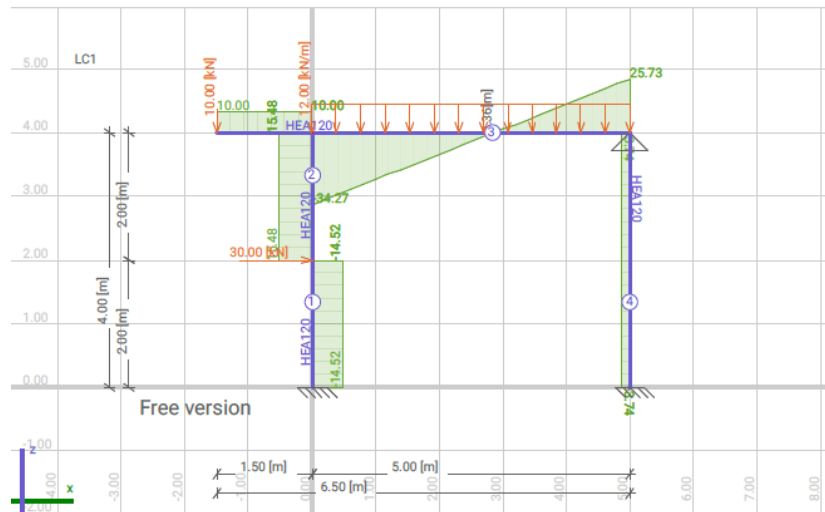


Figure 10. Shear force diagram

3.2 Calculation of 2D Hyperstatic Frame

The process of manually calculating and illustrating axial force, shear force, and bending moment diagrams for 2-dimensional frame structures was carried out in accordance with the lecture notes from the course "Structural Analysis II" by Dr. Fathelrahman Mohamed Adam [22].

Determine known and unknown displacements

$$\theta_1 = 0, \theta_2 = ?, \theta_3 = ?, \theta_4 = 0$$

$$\delta_1 = 0, \delta_2 = 0, \delta_3 = 0$$

Calculate the Stiffness of the element (k)

$$k_1 = \frac{1.5EI}{4} = 0.375EI$$

$$k_2 = \frac{2EI}{5} = 0.4EI$$

$$k_3 = \frac{EI}{4} = 0.25EI$$

Calculate the fixed end moments shown in Figure 11.

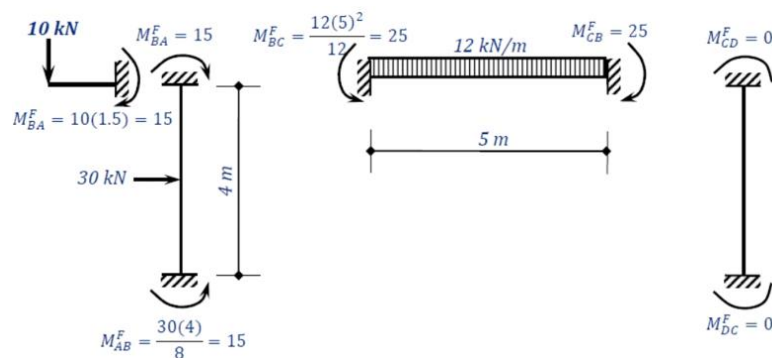


Figure 11. Calculation of the fixed-end moments

Construct matrix

$$\begin{bmatrix} 4(k_1 + k_2) & 2k_2 \\ 2k_2 & 4(k_2 + k_3) \end{bmatrix} \begin{Bmatrix} \theta_2 \\ \theta_3 \end{Bmatrix} = \begin{Bmatrix} -M_{cl} - M_{21}^f - M_{23}^f \\ -M_{32}^f - M_{34}^f \end{Bmatrix}$$

Substitute in matrix

$$EI \begin{bmatrix} 4(0.375 + 0.4) & 2(0.4) \\ 2(0.4) & 4(0.4 + 0.25) \end{bmatrix} \begin{Bmatrix} \theta_2 \\ \theta_3 \end{Bmatrix} = \begin{Bmatrix} -15 - 15 - (-25) \\ -25 - 0 \end{Bmatrix} \quad EI \begin{bmatrix} 3.1 & 0.8 \\ 0.8 & 2.6 \end{bmatrix} \begin{Bmatrix} \theta_2 \\ \theta_3 \end{Bmatrix} = \begin{Bmatrix} -5 \\ -25 \end{Bmatrix}$$

$$\begin{Bmatrix} \theta_2 \\ \theta_3 \end{Bmatrix} = \frac{1}{EI} \begin{Bmatrix} 0.943 \\ -9.906 \end{Bmatrix}$$

Calculate the end moments

Substitute the value of equations (1), (2), (3), and (4).

Element 1:

$$\theta_i = \theta_1 = 0, \quad \theta_j = \theta_2 = 0.943$$

$$M_{12} = 4k_1\theta_1 + 2k_1\theta_2 + M_{12}^f = 0$$

$$M_{12} = 0 + 2(0.375)(0.943) - 15 = -14.3 \text{ kN.m}$$

$$M_{21} = 2k_1\theta_1 + 4k_1\theta_2 + M_{21}^f = 0$$

$$M_{21} = 0 + 4(0.375)(0.943) + 15 = -16.4 \text{ kN.m}$$

Element 2:

$$\theta_i = \theta_2 = 0.943, \quad \theta_j = \theta_3 = -9.906$$

$$M_{23} = 4k_2\theta_2 + 2k_2\theta_3 + M_{23}^f = 0$$

$$M_{23} = 4(0.4)(0.943) + 2(0.4)(-9.906) - 25 = -31.4 \text{ kN.m}$$

$$M_{32} = 2k_2\theta_2 + 4k_2\theta_3 + M_{32}^f = 0$$

$$M_{32} = 2(0.4)(0.943) + 4(0.4)(-9.906) + 25 = 9.9 \text{ kN.m}$$

Element 3:

$$\theta_i = \theta_3 = -9.906, \quad \theta_j = \theta_4 = 0$$

$$M_{34} = 4k_3\theta_3 + 2k_3\theta_4 + M_{34}^f = 0$$

$$M_{23} = 4(0.25)(-9.906) + 0 + 0 = -9.9 \text{ kN.m}$$

$$M_{32} = 2k_3\theta_3 + 4k_3\theta_4 + M_{43}^f = 0$$

$$M_{32} = 2(0.25)(-9.906) + 0 + 0 = -4.95 \text{ kN.m}$$

Calculate the support reactions shown in Figure 12.

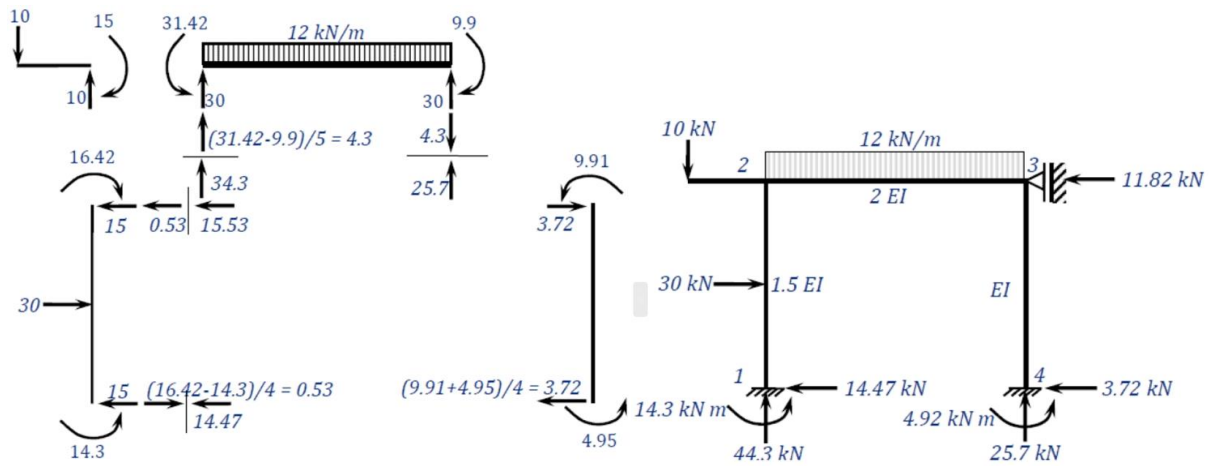


Figure 12. Calculation of the support reactions

Draw bending moment and shear force diagrams shown in Figure 13 and Figure 14.

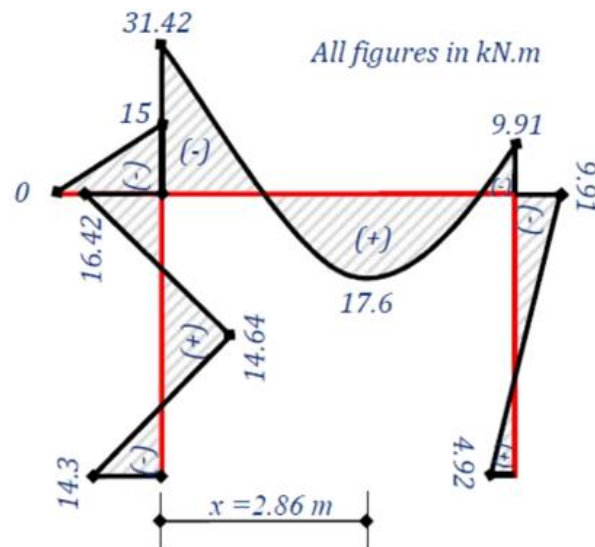


Figure 13. Bending moment diagram

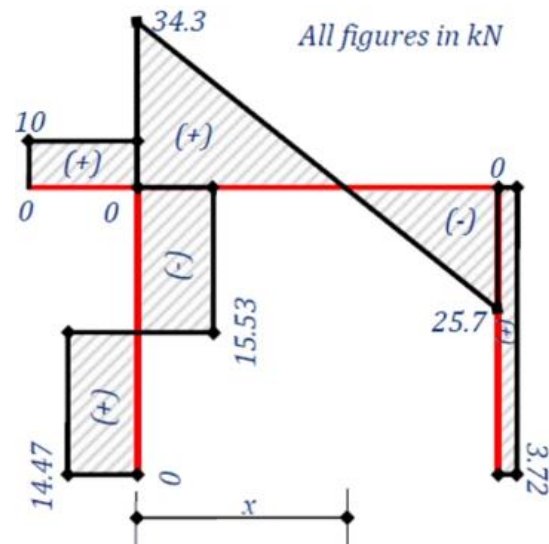


Figure 14. Shear force diagram

For x:

$$x = \frac{34.3}{12} = 2.86 \text{ m}$$

$$M_x = -31.42 + 34.3(2.86) - \frac{12(2.86)^2}{2} = 17.6 \text{ kN.m}$$

$$M_{30} = -14.3 + 14.47(2) = 14.64 \text{ kN.m}$$

3.3 Validation of Finite Element Analysis using SAP 2000

The accuracy of the results obtained from the paper of the 2-dimensional frame structure utilizing the Frame Design Application was further verified by using SAP2000 Software. The paper outcomes conducted using SAP2000 Software for the axial force are depicted in Figure 15. At the same time, the bending moment diagram is illustrated in Figure 16, and the shear force diagram is displayed in Figure 17. The observed disparities in the outcomes of the analysis conducted in the Frame Design Application, manual analysis, and analysis using SAP2000 Software for axial force, bending moment, and shear force are evident. However, these variations are not deemed significant, as the value discrepancies do not exceed 1%.

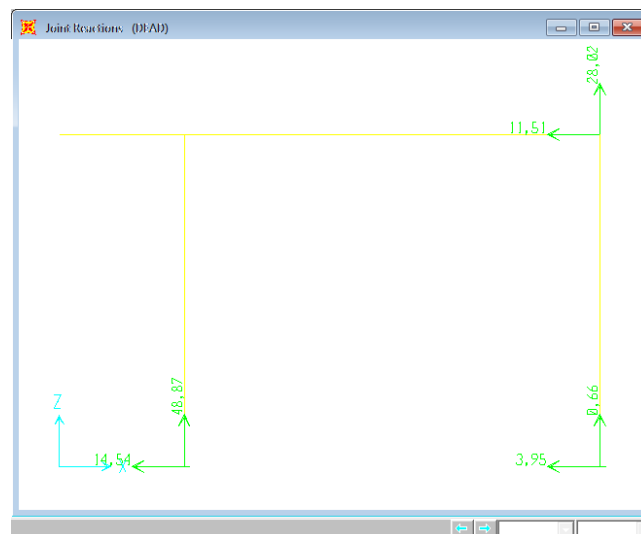


Figure 15. Axial force

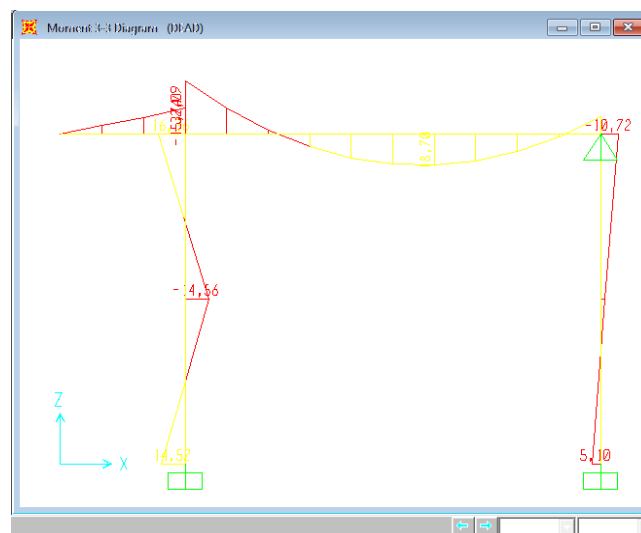


Figure 16. Bending moment diagram

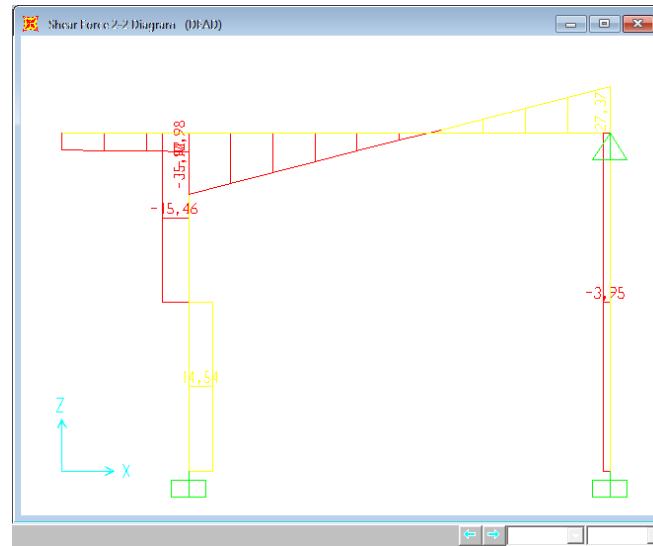


Figure 17. Shear force diagram

4. Conclusion

This paper examines 2-dimensional frame structures using the Frame Design Application. Manual calculations and the utilization of SAP2000 Software evaluate the accuracy of the results. The provided analysis results exhibit negligible disparities. The Frame Design Application is a highly recommended tool for those in civil engineering, mechanical engineering, architecture, and students seeking to design 2D hyperstatic frames through the utilization of Finite Element Analysis (FEA).

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