Delta University Scientific Journal
Journal home page: https://dusj.journals.ekb.eg

Optimal Spacing and Grouping Recommendations for Transmission Line Systems

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ABSTRACT
Transmission towers play a crucial role in the development of modern communities and the expansion of infrastructure projects, especially in developing countries that prioritize power development programs. To ensure the structural integrity and performance of these towers, numerical as well as finite element analysis have been conducted to investigate their load-bearing capacity and failure mechanisms under various loading conditions.

This research work focuses on the optimization of transmission tower design, specifically targeting the reduction of overall weights through the implementation of unconventional grouping systems. Additionally, the study aims to determine the most suitable tower spacing for the entire transmission line, considering various parameters. The towers under investigation are classified as suspension type and are designed to maintain a constant height, common clearances, a consistent span, and standardized conductor and ground wire specifications.

The research follows a systematic approach that involves a comparative analysis between the conventional design practices of transmission towers and the progressively developed investigations. By implementing this sequence of procedures, the study aims to enhance the analysis and design processes of self-supporting 400 KV steel power transmission towers.

The findings of this research will contribute to the optimization of transmission tower designs, resulting in improved structural efficiency and reduced overall weights. By utilizing unconventional grouping systems and identifying the most suitable spacing, the research aims to provide practical solutions that can be implemented in real-world transmission line projects. Ultimately, these enhancement will support the efficient and reliable transmission of electrical power, facilitating the continued development and growth of communities and infrastructure projects

Keywords—*Transmission tower, Optimum spacing, Optimum grouping, FORTRAN program.*

1. Introduction

A transmission tower, also known as a power transmission tower or electricity pylon, is a tall steel structure supporting an overhead power line [1].

This study focuses on the design optimization of transmission towers with the objective of achieving minimal weight. Transmission towers, which are tall structures supporting overhead power lines, play a crucial role in supplying electricity to different regions of a nation. Transmission towers need to be designed carefully to ensure stability and resilience during natural disasters. The height and configuration of the towers, as well as the details of their members and joints, are determined by the user and structural designer.

Transmission towers can be considered as cantilever structures that are fixed at their bases. They are typically made up of steel sections and consist of a conductor, a ground wire subsystem, and subsystems specific to each class of support structure. These towers are used for both high alternating current (AC) and direct current (DC) voltage transmission, and they come in various sizes and shapes.

In the past, mathematical programming methods have been used to optimize the shape and weight of transmission towers. Design variables such as member sectional areas are taken into account for weight optimization. However, the complexity of the optimization process increases with the growing number of design variables, which include nodal coordinates and member lengths [2, 3].

Numerous researchers have made efforts to design and analyze transmission line towers using various configurations and software programs. Comparative analyses of tower heights using different bracing systems for earthquake forces and wind zones have been conducted [4]. Wind loads, response spectrum analysis, and earthquake loads have been considered in the analysis and design of transmission towers. Software programs like ANSYS and STAAD Pro have been used to perform static, modal, and dynamic analysis, as well as to evaluate stress distribution, strain, deformation, and displacement [5-12].

The optimization and design of transmission towers in this study aim to achieve minimum weight by utilizing computer programs written in FORTRAN. These programs, developed by Naguib M, have been verified and demonstrated high reliability compared to other programs in the field [13].

Overall, the objective of this work is to investigate, optimize, and achieve the minimum weight design for transmission towers, considering their crucial role in power transmission and the need for structural stability and resilience.

2. Transmission Tower

In electrical grids, transmission towers play a crucial role in carrying high voltage transmission lines, which are responsible for transporting bulk electric power from generating stations to electrical substations. These towers are designed to safely support the heavy conductors at an adequate height from the ground, ensuring efficient power transmission.

The design of transmission towers is a complex engineering task that requires the application of civil, mechanical, and electrical engineering concepts. Civil engineering principles are employed to ensure the structural integrity and stability of the tower, considering factors such as wind loads, seismic loads, and soil conditions. Mechanical engineering principles come into play in designing the tower to withstand the weight of the conductors and other components, while also considering factors like material strength, load distribution, and tower configuration. Electrical engineering concepts are applied to determine the appropriate clearance and insulation requirements to maintain electrical safety.

Moreover, transmission towers are engineered to withstand various types of natural disasters, such as strong winds, ice storms, and earthquakes. The design process involves considering the specific environmental conditions and geographical location to ensure the towers can withstand these hazards.

2.1. Transmission Tower Components

The transmission tower, being a vital part of a power transmission system, comprises several components, as shown in Fig. 1.

2.1.1. Cross Arm

The cross arm is responsible for supporting the transmission conductor (Figure 1-a). Its dimensions are determined based on factors such as the transmission voltage level, configuration, and the minimum bending angle required for stress distribution.

2.1.2. Transmission Tower Body

This section extends from the lower cross arms to the ground level (Figure 1-b). It plays a critical role in maintaining the necessary ground clearance for the lower conductor of the transmission line.

2.1.3. Cage of the Transmission Tower

Located between the tower body and the peak, the cage (Figure 1-c) securely holds the cross arms in place.

2.1.4. Peak of the Transmission Tower

Situated above the upper cross arm, the peak (Figure 1-d) serves as the uppermost part of the tower. Typically, an earth shield wire is connected to the peak through an earth arm.

These components collectively contribute to the structural integrity and functionality of the transmission tower within the power transmission system.

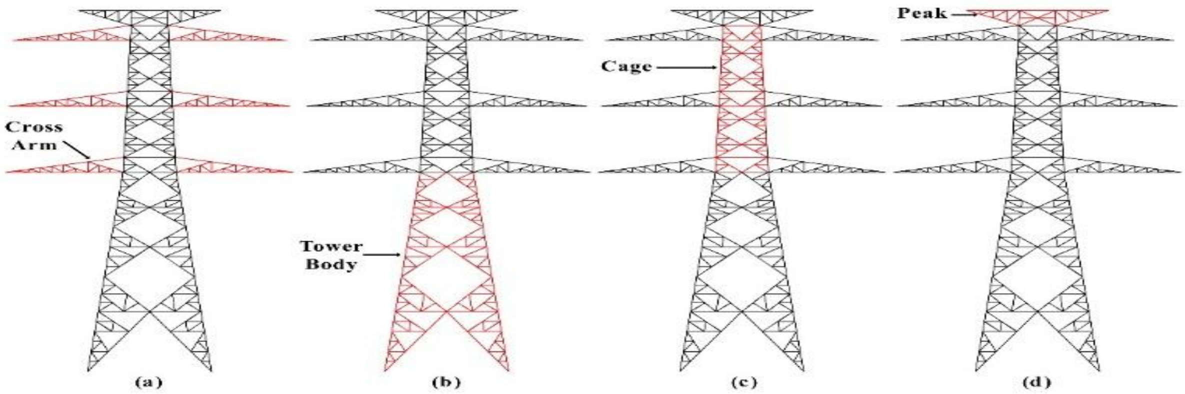


Fig. 1: Transmission tower parts a- Cross arm b - tower body c- cage d-peak

2.2 Transmission Tower Model Dimensions

For the purpose of this study, data specific to a 400 KV transmission line tower is utilized. The focus of the study is on the tower's body, which is subjected to vertical loads. A parametric analysis is conducted to investigate the impact of different element cross-sections on the weight of the tower. To facilitate this analysis, various groupings of elements are formed, where each group consists of members with identical cross-sectional areas and other properties. The weight of the structure is then determined under the same vertical load for each grouping. Throughout the study, the height of the tower is kept constant, while variations in the cross-sectional properties of the members are taken into account. Tower’s Geometric Configurations.

As depicted in Figure 2, the tower body has a height of 33.25m. In Figure 3-a, the cross-section plane of the tower is shown, indicating a square shape with dimensions of 14m by 14m at the base level (ground level) and 6m by 6m at the top level, just below the lowest cross arm (Figure 3-b). The cage part of the tower has a height of 24.50m (Figure 2), and its plan view exhibits a square shape measuring 6m by 6m at the bottom (Figure 3-b) and 4.2m by 4.2m at the top (Figure 3-c). The cross arms extend as cantilevers by 13.25m on each side (Figure 3-b) and are connected to the tower at heights of 33.25m, 44.25m, and 55.25m. At the top, there is a separate arm specifically designed for the earth wire cable.

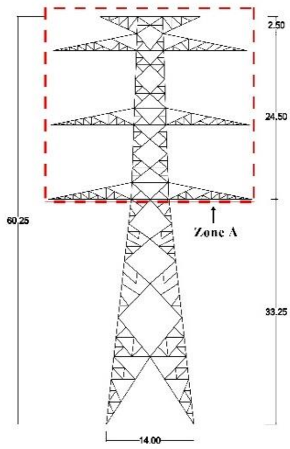
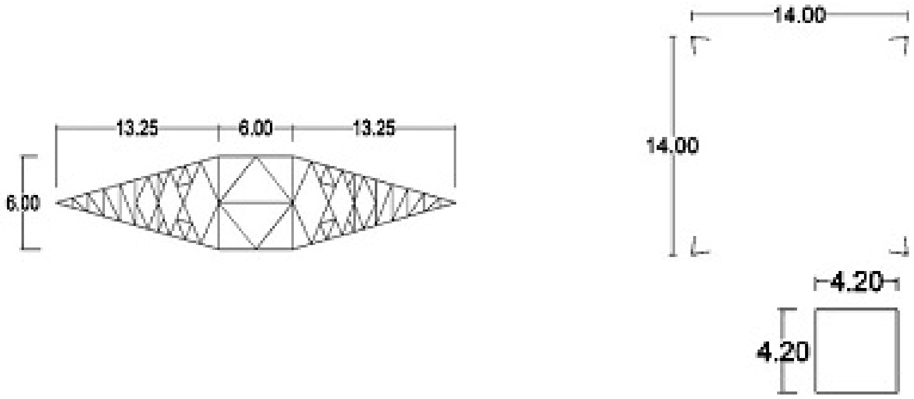


Fig. 2: Tower geometry



a- Cross section at base level

b- Cross section at lower cross arm

c- Cross section at top of the cage

Fig. 3: Tower Cross Sections

In this study, the total potential energy (TPE) method was employed to determine the equilibrium of the structure through a repetitive process aimed at minimizing the TPE. The equilibrium state is achieved when the TPE reaches its minimum value. The analysis conducted in this study utilized a computer program written in FORTRAN [13] that implements the TPE method using the conjugate gradient (CG) algorithm. The results obtained from the FORTRAN program were validated by comparing them with those generated by a commercial Finite Element program (SAP2000).

Subsequently, different spans between the towers were investigated to identify the optimum span for the transmission line. Once the optimum span was determined, various groupings of member cross-sections were tested to determine the optimal configuration for the tower. The goal was to identify the most suitable arrangement of member cross-sections that would result in an optimal tower design, considering factors such as structural stability, weight, and performance.

Through this iterative process, the study aimed to find the optimum distance arrangement and cross-section grouping that would yield a structurally efficient and reliable transmission line system.

3. Loads on Transmission Structures

In accordance with prevailing practices and regulations, the design of transmission tower lines is typically required to meet the minimum standards outlined in the current edition of the National Electrical Safety Code (NESC). The NESC provides guidelines and regulations aimed at ensuring the safety of electrical installations.

The NESC includes rules for selecting capacity factors for loads and overloads, which are intended to establish a minimum level of safety that must be met. These rules take into consideration various factors such as the capacity of the transmission line and the anticipated loads it will carry. The design of transmission lines is expected to meet the minimum safety requirements and ensure the reliable and efficient operation of the electrical system.

3.1 Vertical Loads

The vertical load on supporting structures consists of the weight of the structure plus the superimposed weight (including all wires).

Vertical Wire Load On Structure= V_m*Vertical Design Span*Load Factor………………….. (1)

$Vertical\ Wire\ Load\ On\ Structure = V_m * Vertical\ Design\ Span * Load\ Factor$ **Where:**

- V_m : Vertical load of wire in. (t/m)
- Vertical design span (V): is the distance between low points of adjacent spans and is indicated in (Fig. 4).

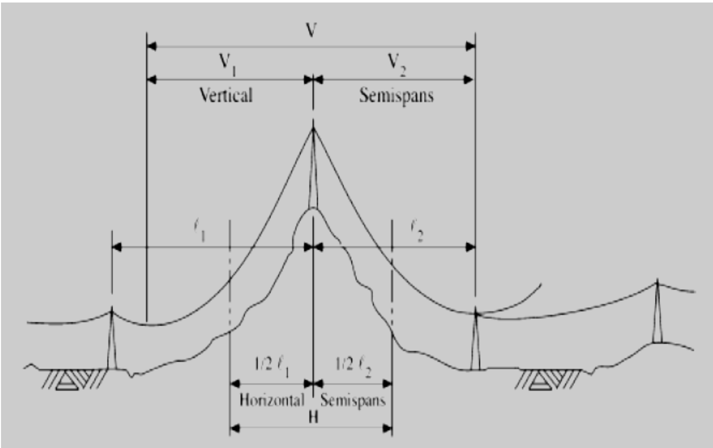


Fig. 4: Indication of vertical design span.

For the case study, the loads were carried out by the previous formula and the calculated loads on the tower for 550 m spacing transmission line are shown in (Fig. 5).

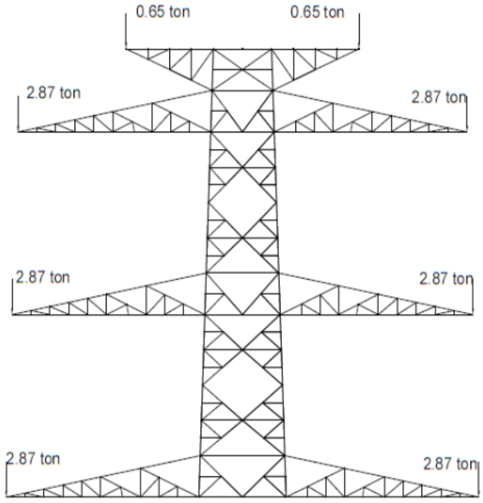


Fig. 5: Example of determination of vertical design load for the tower under consideration (Zone A).

4. Fortran Program Verification

To validate the accuracy of the FORTRAN program, a model with identical geometry and loading conditions was created in both the FORTRAN program and SAP2000. Specifically, the deflection of the cross arm and the internal forces for members in each group were examined to compare the results obtained from the FORTRAN program with those generated by SAP2000, as depicted in Figure 5.

The comparison of the deflection results from the two programs, as shown in Figure 6, demonstrated a high level of agreement.

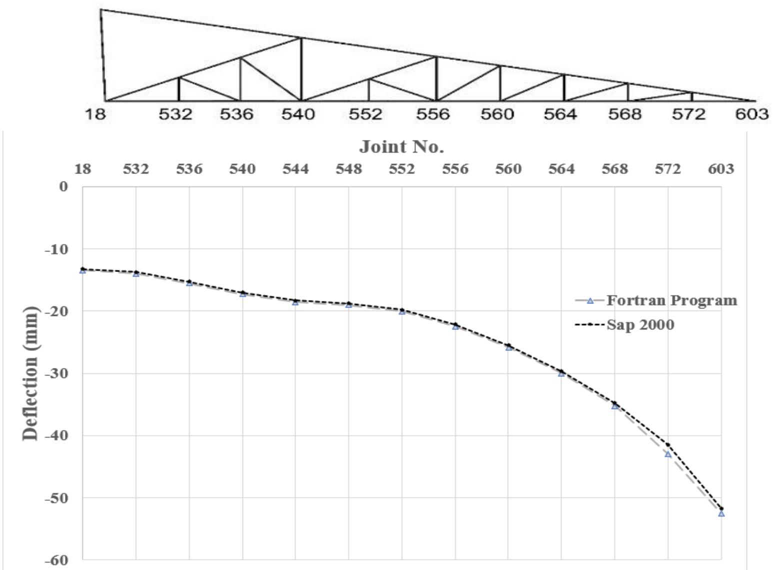


Fig. 6: Cross arm deflection verification between SAP 2000 and FORTRAN program.

The comparison of the internal forces results for members in each group from the two programs, as shown in Figures (7, 8, and 9) demonstrated a high level of agreement.

This indicates that the FORTRAN program effectively captured the structural behavior and accurately predicted deflection for cross arm and internal forces for members. The agreement between the two programs further reinforces the reliability and accuracy of the FORTRAN program in analyzing and predicting the behavior of the transmission tower structure.

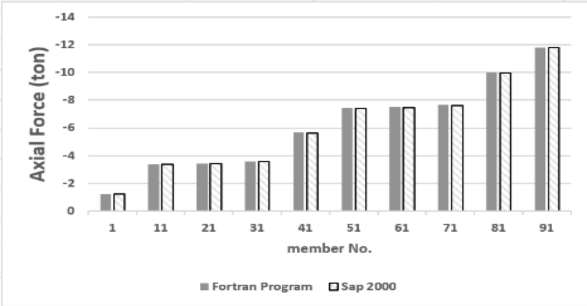


Fig. 7: Axial force for member group 1.

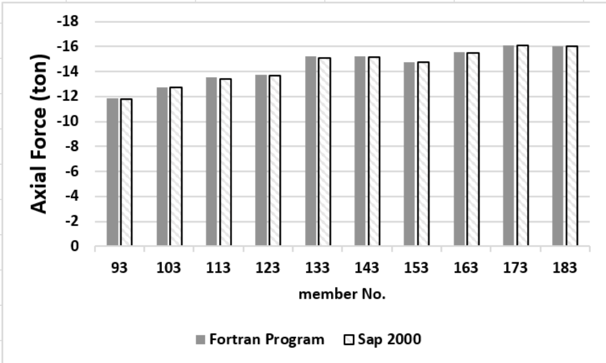


Fig. 8: Axial force for member group 2.

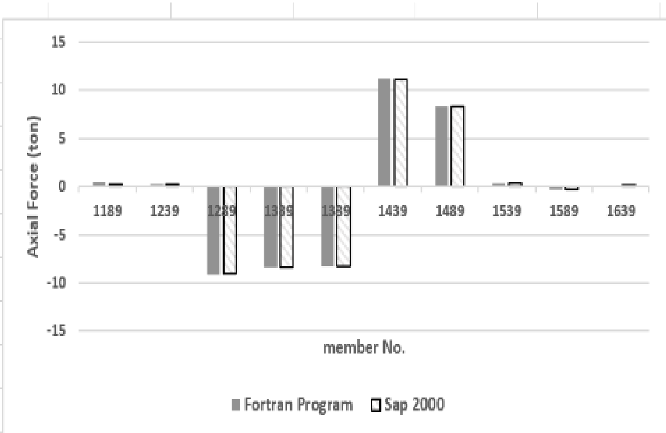


Fig. 9: Axial force for member group 3

5. Optimization According to Spacing in Transmission Line

The analysis involved four models using the FORTRAN program, each having the same shape, and dimensions but varying in the spacing between the towers. The spacing between the towers directly influences the load acting on the tower.

In each model, the tower was divided into three groups, and each group initially assumed its own cross section. Subsequently, the design process was carried out for each group based on the resulting internal forces, and the cross sections were redefined to obtain the actual deflection and internal forces for each model.

Figure 10 illustrates the deflection of the cross arm for different tower spacing. It is observed that, using the traditional grouping method with three groups, larger tower spacing generally resulted in increased deflection for each cross arm. Specifically, at the critical point located at the end of the cross arm, the deflection increased by approximately 17.3%, 38.7%, and 41.3% for spans of 250m, 350m, and 450m, respectively, compared to the base span of 550m.

These findings highlight the influence of tower spacing on the deflection behavior of the transmission tower, with larger spacing resulting in increased deflections. This information is valuable for optimizing the design of transmission towers to ensure they meet the desired deflection criteria and structural stability under different spacing conditions.

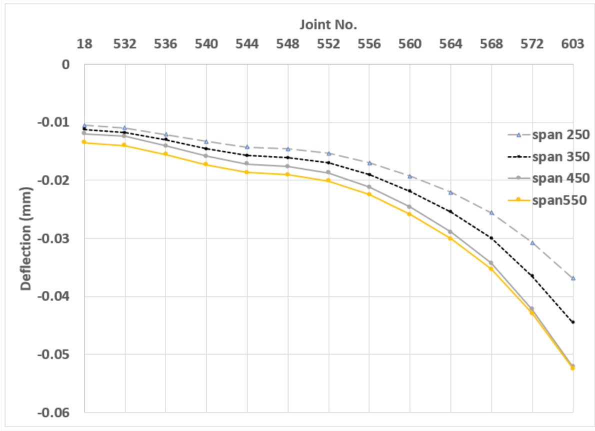


Fig. 10: Cross arm numbering and deflection for different tower spanning.

In terms of the total line weight (T.L.W.), as presented in Table 1, it was observed that when using the traditional grouping approach (three-group), larger spans resulted in lower weights up to a span of 350m. However, for spans of 450m and 550m, there was only a slight difference in weight.

Table 1: Single tower weights and total line weights for different spans for 173250 m transmission line

Span (m)	Single tower weight (ton)	No. of towers	Total line weight (ton)
550	53.183	315	16752.65
450	43.534	385	16760.59
350	43.534	495	21549.33
250	43.534	693	30169.06

Taking into consideration the overall deflection behavior, Span 450m was chosen as the optimized span. This decision was based on the fact that it exhibited lower deflection compared to Span 550m, as shown in Figure 10.

By selecting Span 450m as the optimized span, it is possible to achieve a balance between reducing deflection and minimizing the total line weight. This information is valuable for making informed decisions in the design process of transmission towers, ensuring structural stability and optimal performance under different span configurations.

To further optimize the tower design, the cross-section of the tower members is divided into more groups. Initially, a tower with a span of 450m is divided into three groups following the traditional approach. In this division, the main legs of the tower are split into two groups, while all other members are considered as one group, as illustrated in Figure 11.

This finer division of the tower member cross-section allows for more precise analysis and design optimization. By grouping the members based on their specific characteristics and load-carrying capacities, it becomes possible to fine-tune the design to achieve better structural performance and minimize weight while maintaining structural integrity and stability.

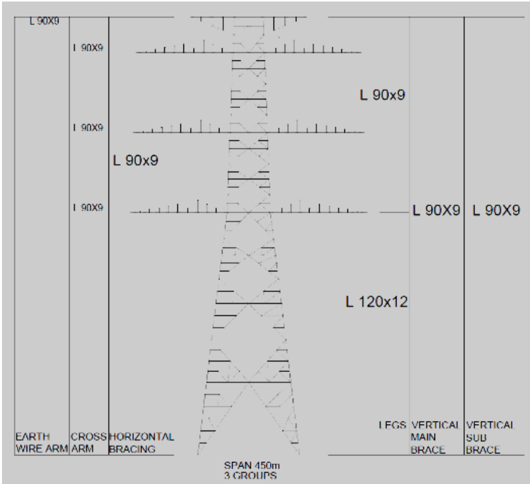


Fig. 11: 450 m span tower divided into 3 groups.

For more optimization, the optimum tower was divided into more groups as shown in (Fig. 12, six groups) and (Fig. 13, eleven groups).

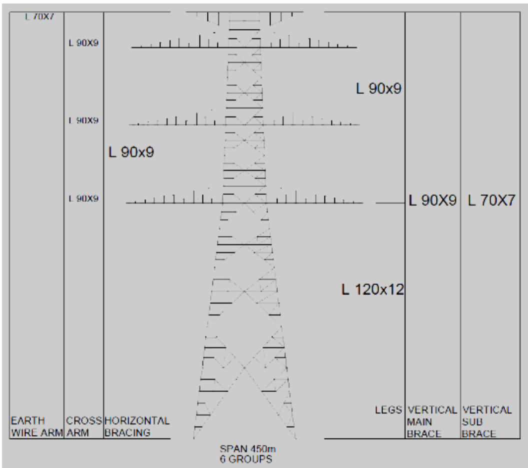


Fig. 12: 450 m span tower divided into 6 groups.

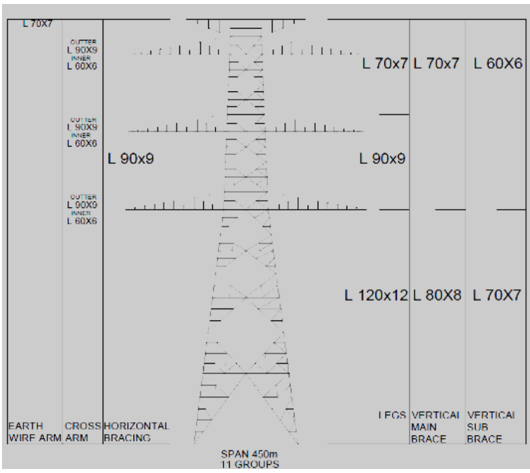


Fig. 13: 450 m span tower divided into 11 groups.

In the case of the most optimized span (450m), dividing the weight of a single tower (S.T.W) into 11 group leads to a further decrease in deflection compared to the 3 and 6 groups. Specifically, the deflection is reduced by approximately 6% compared to the 3-group division, and by about 2% compared to the 6-group division, as depicted in Figure 14.

This observation suggests that increasing the number of groups in the tower design can contribute to a stiffer composition. By dividing the tower weight into more groups and optimizing the cross-section of each group accordingly, the overall deflection can be further minimized. This highlights the importance of considering a more detailed and refined approach to grouping tower members for achieving superior structural performance and reduced deflection.

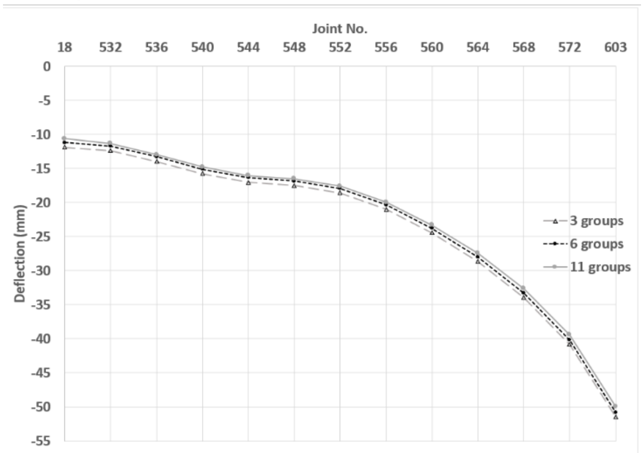


Fig. 14: Cross arm deflection for different groping groups.

In the case of the most optimized span (450m), dividing the weight of a single tower into 11 groups results in a significant decrease in the total tower weight (S.T.W) compared to the 3 and 6 group divisions. Specifically, the weight is reduced by approximately 24% compared to the 3-group division, and by about 12% compared to the 6-group division, as shown in Figure 15.

This finding indicates that increasing the number of groups in the tower design can lead to a more efficient utilization of materials, resulting in a lighter overall structure. By optimizing the cross-section of each group and distributing the load more effectively, the weight of the tower can be significantly reduced. This demonstrates the potential benefits of employing a more detailed and refined grouping approach for achieving a lighter and more cost-effective transmission tower design.

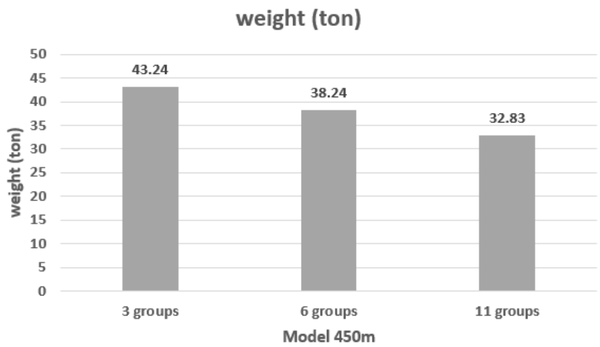


Fig. 15: Weights of tower for different grouping systems.

6. Conclusion

In conclusion, this manuscript has successfully addressed several important aspects related to the design and optimization of transmission line towers. The key findings and implications of this study can be summarized as follows:

- The accuracy and reliability of the FORTRAN program used for structural analysis were verified through a comparison with results obtained from the commercial software SAP2000. The high level of agreement between the two programs indicates that the FORTRAN program effectively captures the structural behavior and can be relied upon for tower design and analysis.
- By increasing the number of groups in the tower design, a more economic cross-sectional design can be achieved. The division of the tower weight into 11 groups resulted in a significant reduction of more than 24% in the overall cost compared to the 3-group division. This highlights the importance of considering a detailed and refined grouping approach for optimizing the structural design and minimizing material consumption.
- Taking into account both serviceability and economic considerations, a span of 450 m was identified as the most optimized spacing for a transmission line system. This span demonstrated lower deflection and overall line weight compared to larger spans of 550 m. Therefore, it can be recommended as the optimal spacing for achieving a balance between structural performance and cost-effectiveness.
- Overall, this study provides valuable insights into the design and optimization of transmission line towers. The findings contribute to enhancing the efficiency and cost-effectiveness of transmission line systems, ultimately benefiting the power transmission industry and ensuring reliable electricity supply to various regions.

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