Research of fastener distribution for typical irregular connections of civil aircraft

Pengpo Gou*

1Manufacturing Support Engineering Department, Shanghai Aircraft Design and Research Institute, Shanghai, 201220, China
*goupengpo@163.com

Abstract. In this paper, based on the analytical method of calculating simple and regular single shear connector distribution, based on the engineering formula, the flexibility coefficient of different fasteners, pin spacing, plate width and plate thickness is given. The deformation coordination equation between adjacent fasteners is established. The diameter of different fasteners is given by the equilibrium conditions of the binding force. The calculation equations of fastener load distribution under the spacing of fastener, plate width and plate thickness have been calculated. The finite element model for calculating fastener load is established in finite element software based on finite element method. The calculation results of finite element method and analytical method are compared, and the analytical method is proved to be used to calculate plate width, plate thickness, fastener diameter, and the analysis method. The effectiveness of pin load distribution for typical connection structures with constant spacing between Fasteners is also presented.

1. Introduction

Fastener is the most connection method used in aircraft manufacturing. For the nail load analysis of the multi-fastener connection structure in civil aircraft, the analytical method and finite element method are mainly used in engineering. The analytical method can get a more accurate nailing distribution for simple and regular connection structures. The finite element method can accurately obtain the nail load distribution of most connected structures through modelling, but the modelling process takes a long time, and a model can only be analysed for a single structure. Therefore, for the irregular connection structure in the actual structure, it is necessary to obtain a reliable, fast, and widely applicable nailing calculation method.

2. Analytical method of connecting irregular structure nail load distribution

2.1. Structure Type

The irregular structure of the single shear connector is shown in Figure 1.
The meaning of the symbols in Figure 1 is as follows:

- $D_i$ —— the diameter of the $i$th nail;
- $S_i$ —— the distance between the $i$th nail and the $(i+1)$th nail (load direction);
- $n$ —— number of nail rows;
- $t_{si}$ —— the thickness of the strip between the $i$th nail and the $(i+1)$th nail;
- $t_{pi}$ —— the thickness of the substrate between the $i$th nail and the $(i+1)$th nail;
- $W_{si}$ —— the width of the strip between the $i$th nail and the $(i+1)$th nail;
- $W_{pi}$ —— the width of the base plate between the $i$th nail and the $(i+1)$th nail;
- $P$ —— external load.

The meanings of other parameters are as follows:

- $C_i$ —— the flexibility coefficient of the $i$th nail;
- $F_{si}$ —— the flexibility coefficient of the strip between the $i$th nail and the $(i+1)$th nail;
- $F_{pi}$ —— the flexibility coefficient of the substrate between the $i$th nail and the $(i+1)$th nail;
- $E_s$ —— the elastic modulus of the strip;
- $E_p$ —— the elastic modulus of the substrate;
- $R_i$ —— the load of the $i$th nail.

2.2. Basic assumption

1. The structures are all within the elastic range;
2. Ignore the influence of friction and assembly clearance;
3. The stress is evenly distributed along the cross section of the plate.

2.3. Deformation coordination equation

The deformation coordination equation can be understood as the deformation between any two adjacent nails to be coordinated, that is, the deformation of the nail between the two nails of one plate + the deformation of the plate = the deformation of the nail between the two nails at the corresponding position of the other plate + the deformation of the plate.

For the single shear connector, the nail deformation, plate deformation and plate load are shown in Figure 2.
Therefore, the deformation coordination relationship between the i-th nail and the i+1-th nail can be obtained:

\[
\Delta_{yi} + L + \Delta_{yi} = \Delta_{y(i+1)} + L + \Delta_{y(i+1)} \quad \text{........................................(1)}
\]

Among them, the load on the strip between the i-th nail and the i+1 nail is \(P - \sum R_i\), and the load on the substrate is \(\sum R_i\), then the deformation of the i-th nail, the deformation of the i+1 nail, the deformation of the strip and the substrate are respectively:

\[
\Delta_{yi} = C_i R_i \\
\Delta_{y(i+1)} = C_{i+1} R_{i+1} \\
\Delta_s = F_s \left( P - \sum_{j=1}^{i-1} R_j \right) \quad \text{........................................(2)}
\]

\[
\Delta_p = F_p \sum_{j=1}^{i} R_j
\]

Put the nail load \(R_i\) on the right side of the equation, and only the external load \(P\) is simplified on the left side of the equation, and the following n-1 equations can be obtained:
2.4. Force balance condition

The force balance condition means that the sum of the load of each nail should be equal to the external load, and its expression is as follows:

\[ R_1 + R_2 + \cdots + R_n = P \] ........................................(4)

Combining the previous \( n-1 \) equations and taking the external load \( P \) as 1, the ratio \( R_i/P \) of each nail load to the external load can be obtained.

2.5. Engineering calculation method of flexibility coefficient

According to the previous analysis, the nail load distribution is related to the flexibility coefficient \( C_i \) of each nail, the flexibility coefficient of each strip \( F_s^i \) and the flexibility coefficient of the substrate. The calculation method of the nail flexibility coefficient and board flexibility in the project is given below.

2.5.1. Nail flexibility coefficient.

According to reference [1], for the single shear connection as shown in Figure 3, when the connecting plate is made of aluminum alloy, the nail flexibility coefficient \( C \) can be determined by the following formula:

\[ C = \frac{K_{de}}{t_2 E} \left( 14.7 - 0.8D \right) \left( \frac{t_2}{t_1} \right)^{0.456} \] ..................................(5)

The meaning of each parameter in the formula is as follows:
t₁—the thickness of the thinner plate;
t₂—the thickness of the thicker plate;
Kdc—nail material correction factor; for aluminium nails, Kdc=1; for titanium nails, Kdc=0.77; for steel nails, Kdc=0.67.

2.5.2. Board flexibility coefficient.
According to the reference [1], the formulas of the strip flexibility coefficient Fₛ and the substrate flexibility coefficient Fₚ are as follows:

\[
F_s = \frac{S}{W_t E_s} \\
F_p = \frac{S}{W_p E_p}
\]

(6)

For the flexibility coefficient of each strip Fₛᵢ and the substrate flexibility coefficient Fₚᵢ, the parameters in the formula are the width and thickness of each strip or substrate.

3. Analytical method verification of typical connection irregular structure nailing distribution

3.1. Verification method
Since the finite element method can simulate the approximate irregular structure (structures with different nail diameter, nail spacing, plate width and plate thickness) through modeling well, the finite element method introduced in references [2] and [3] will be used. The meta-method derives four kinds of nail load distributions of irregular structures, which is used to verify the applicability of the analytical method of typical connection irregular structure nail load distributions in this article. The four types of irregular structures all change only one type of parameters of the simple-shear connection rule structure. The specific parameters of the simple-shear connection rule structure are shown in Table 1, and the finite element model is shown in Table 2. With uniformly distributed loads, the modeling process of irregular structures is the same as that of regular structures, only the geometric parameters of the model are modified.

| Fastener | Nails Number | Nail Diameters /mm | Nail Elastic Modulus/MPa |
|----------|--------------|---------------------|--------------------------|
| 4        | 4.76         | 70000 (Aluminum Alloy) |

| Connecting Plate | Plate Width/mm | Plate Length/mm | Tip Distance/mm | Nail Spacing/mm |
|------------------|----------------|-----------------|-----------------|-----------------|
| 24               | 120            | 12              | 20              |
| 3                | 70000 (Aluminum Alloy) |

3.2. Irregular structure of simple shear connection

3.2.1. Different nail diameters.
For verification examples with different nail diameters, compared with the simple shear connection example in Table 1, only D1 is 5.56mm. The comparison of the results obtained by the analytical method and the finite element method in this paper is shown in Table 2.

| Method                      | D1=5.56 R1/P | D2=4.76 R2/P | D3=4.76 R3/P | D4=4.76 R4/P |
|-----------------------------|--------------|--------------|--------------|--------------|
| The analytical method       | 0.298457     | 0.232979     | 0.222079     | 0.246485     |
| The finite element method   | 0.289417     | 0.236686     | 0.227372     | 0.246525     |
| Method Error                | 3.1235%      | -1.5662%     | -2.3279%     | -0.0162%     |

3.2.2. Different nail spacing.
For the verification example with different nail spacing, compared with the simple shear connection example in Table 1, only S1 is 24mm. The comparison of the results obtained by the analytical method and the finite element method in this paper is shown in Table 3.

| Method                      | S1=24 R1/P | S2=20 R2/P | S3=20 R3/P | S4=20 R4/P |
|-----------------------------|------------|------------|------------|------------|
| The analytical method       | 0.293492   | 0.235016   | 0.22365    | 0.247841   |
| The finite element method   | 0.285831   | 0.238288   | 0.228417   | 0.247464   |
| Method Error                | 2.6803%    | -1.3731%   | -2.087%    | 0.1523%    |

3.2.3. Different board width.
For the verification example with different board widths, compared to the single-shear connection example in Table 1, the board width from the end of the board to the first nail is 16mm, and the board width between the first nail and the second nail increases linearly to 24mm, The board width between the second nail and the third nail is 24mm, and the board width between the third nail and the fourth nail decreases linearly to 16mm. The results obtained by the analytical method and the finite element method are compared in Table 4.

| Method                      | W1=20 R1/P | W2=24 R2/P | W3=20 R3/P |
|-----------------------------|------------|------------|------------|
| The analytical method       | 0.296644   | 0.234996   | 0.224128   | 0.244233   |
| The finite element method   | 0.291994   | 0.237683   | 0.226237   | 0.244086   |
| Method Error                | 1.5925%    | -1.1305%   | -0.9322%   | 0.0602%    |

3.2.4. Different plate thickness.
For the verification examples with different plate thicknesses, compared to the simple shear connection example in Table 1, the strip thickness decreases linearly from 2mm at the first nail to 1.1mm at the fourth nail, and the substrate thickness increases linearly from 3mm at the first nail. To 3.9mm from the 4th nail, the results obtained by the analytical method and finite element method in this paper are compared in Table 5.
Table 5 Comparison of results with different plate thicknesses

| Method                  | $t_s^1=2$ | $t_p^1=3$ | $t_s^2=1.1$ | $t_p^2=3.9$ |
|-------------------------|-----------|-----------|-------------|-------------|
|                         | $R_1/P$   | $R_2/P$   | $R_3/P$     | $R_4/P$     |
| The analytical method   | 0.311031  | 0.253122  | 0.221836    | 0.214011    |
| The finite element method| 0.30798   | 0.257016  | 0.225428    | 0.209576    |
| Method Error            | 0.9908%   | 1.5152%   | 1.5933%     | 2.1161%     |

3.3 Verification conclusion

Through the above comparison, it can be seen that for typical irregularly connected structures, the nail load distribution results obtained by the analytical method in this paper are not very different from the finite element results, and the maximum error is 3.1%, and the accuracy meets the engineering requirements.

4. Summary and outlook

Based on the research on the nail load distribution of fasteners with typical connection irregular structures, this paper found that the error between the nail load distribution obtained by the analytical method and the nail load distribution obtained by the finite element method based on the engineering formula is not more than 3.1%. The error meets the accuracy of general engineering calculations. For the calculation of the nail load distribution of fasteners with typical irregular connections, a faster and simpler analytical method can be used instead of the complex finite element method. Through the research of this article, the scope of application of the analytical method has been expanded, and it also provides a faster and more accurate method for the engineering calculation of the nail load distribution of the typical connection irregular structure.

References

[1] Yuan Huasheng, Xu Zhongnian. (2003) Use PATRAN/NASTRAN software for internal force analysis of connectors[J]. Civil Aircraft Design and Research. (02): 15-18

[2] Chen Haihuan, Liu Hanxu, Li Zejiang. (2012) Finite element calculation and analysis of multi-nail connection of aircraft structure[J]. Advances in Aeronautical Engineering. (04):457-462

[3] Zheng Xiaoling, Li Lingfang. (2003) Design Manual for Durability and Damage Tolerance of Civil Aircraft Structure (Volume One) Fatigue Design and Analysis[M]. Beijing: Aviation Industry Press. Beijing.