Reliability-Based Design of Solid and Nail-jointed I-Section of Nigerian-Grown African Birch (Anogeissus leiocarpus) Timber Column

*1WILSON, UN; 2ADEDEJI, AA; 1ORIOLA, FOP; 3ALOMAJA, JA; 1SANI, JE

*1Department of Civil Engineering, Nigerian Defence Academy Kaduna, Nigeria.
2Department of Civil Engineering, University of Ilorin, Ilorin, Nigeria.
3Department of Civil Engineering, Adeleke University Ede, Nigeria.
*Corresponding Author Email: unwilson@nda.edu.ng

Abstract: The Nigerian-grown African birch timber was used to assemble I- section specimens which were tested in the laboratory for their compressive strengths. Solid square sections of the same specie were similarly tested for an apt comparison of results. A structural reliability analysis was carried out for these two sections to ascertain their performance as structural timber columns using statistical parameters that were determined for the deterministic design of the timber column. A FORTRAN-based program was also developed and used for the reliability analysis of the Nigerian-grown African birch columns designed to ascertain their level of safety using First-Order Reliability Method (FORM). The ‘I’-section was found unsafe to bear the design load unlike its corresponding solid section. An identified I- section of (100 x 400mm) was found adequate (with P =1.22 x 10^6) whose compressive resistance corresponds to (200 x 100mm) of the solid section (with P =7.76 x 10^6) which is practically half the dimension of the I-section. This shows that the solid section has a capacity twice that of the ‘I’-section of equal dimensions. However, considering the minimum dimension of the of the two sections capable of supporting the design load, the ‘I’-section is more economical than the solid section since it offers a less effective area of 11,200mm² compared to the solid section with an effective area of 20,000mm². The ‘I’-section also showed a higher capacity to bear the Euler load with greater lengths than the solid section because of its greater radius of gyration and rigidity value and would be rather preferable for long columns than the solid section. Considering the limited availability of larger dimensions of solid sections, the built-up I- section would be more relevant where large sized sections are required.

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the timber strength is of utmost importance to the engineer since the structural element is not designed as a composite material so to speak in that the materials used are same. Usually, the individual members joined together to make up the laminated or built-up sections are carefully selected such that they are of excellent properties and truly representative of the ideal condition of the timber. This is done for the purpose of having a resultant section with equally excellent properties usually relative to the corresponding solid section. By doing these, timber as a material is to some extent made to become semi-artificial in that it can be fabricated into different geometrical configurations like I-sections, box-sections, T-sections, rectangular sections, square sections. Also, the size of the sections can be increased beyond the naturally available sizes of the timber or beyond the standard preferred sizes in which they are converted to. Consequently, the load carrying capacity (that is moment capacity for beams, compressive and buckling resistance for columns) of the timber would be increased thereby maximize the timber as a construction material.

Wilson et al (2018) in a study on a reliability-based design of a solid African birch timber column showed that the Nigerian grown African birch is a satisfactory structural material for use as solid timber columns at a depth and breadth of 150mm, effective length of 3600mm and an axial load of 260kN; with a probability of failure $8.85 \times 10^{-3}$. It was discovered that a column of similar effective length can at a depth of 400mm, breadth of 200mm support an axial load of 1000kN with a probability of failure of $4.85 \times 10^{-2}$.

The reliability by failure rate method was also considered and it was observed that the Nigerian grown African birch has a higher failure rate at an interval of 10 years over a 100 years expected lifespan in bending when compared to compression and this can be attributed to their respective basic compressive and bending strength values. Aguwa and Sadiku (2011) from a reliability studies showed that the Nigerian Ekki (Lophira alata) timber is a satisfactory structural material for timber bridge beams at depth of 400 mm, breadth of 150 mm and span of 5000 to 7000 mm under the ultimate limit state of loading. Its probability of failure in flexure under the specified operating conditions is $1.1 \times 10^{-7}$, that is, one in ten million. If an optimization was carried out, a more economical section and span would have been found. Aguwa (2012) showed from a reliability studies that the Nigerian grown Apa (Afzelia bipindensis) timber is a satisfactory structural timber for bridge beams at depth of 400mm, breadth of 150mm and span of 5000mm under the Ultimate Limit State of Loading.

The limit state or performance function in compression as given by (Nowak and Collins 2000) \[ g(x) = f_{p,par} - f_a, \] where $f_{p,par}$ is the design stress and $f_a$ is the actual stress.
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Where: $f_{p\parallel} =$ Permissible stress parallel to grain; $f_{a\parallel} =$ Actual stress parallel to grain

From the basic stress gotten for the solid timber, the limit state function can be written as

$$g(x) = 16.25 - \frac{N}{bh} \quad (2)$$

Wilson et al., (2018)

To consider the reliability of the timber with an interest in considering the length in response to the performance, the limit state function formulated from the Euler load formula and can be given by

$$g(x) = 16.25 - \frac{9.23 E r^2}{l^2} \quad (3)$$

Where: $E =$ Youngs’ Modulus of elasticity; $r =$ radius of gyration; $l =$ length of the column

Wilson et al., (2018)

From the basic stress gotten for the I-section timber, the limit state function can be written as

$$g(x) = 9.23 - \frac{N}{bh} \quad (4)$$

To consider the reliability of the I-section timber column with an interest in considering the length in response to the performance, the limit state function formulated from the Euler load formula and can be given by

$$g(x) = 9.23 - \frac{9.23 E r^2}{l^2} \quad (5)$$

Plate 2 Solid Section Test Specimen

Table 3 Probability distribution and Statistical parameters for the basic variables for I-Section of Timber.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Parameters</th>
<th>Distribution</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Load (N)</td>
<td>Log</td>
<td>250</td>
<td>35</td>
<td>0.14</td>
</tr>
<tr>
<td>2.</td>
<td>Breadth (mm)</td>
<td>Normal</td>
<td>150</td>
<td>9</td>
<td>0.06</td>
</tr>
<tr>
<td>3.</td>
<td>Depth (mm)</td>
<td>Normal</td>
<td>150</td>
<td>9</td>
<td>0.06</td>
</tr>
<tr>
<td>4.</td>
<td>Young’s Modulus (N/mm²)</td>
<td>Log Normal</td>
<td>10,500</td>
<td>315</td>
<td>0.03</td>
</tr>
<tr>
<td>5.</td>
<td>Length (mm)</td>
<td>Normal</td>
<td>3600</td>
<td>432</td>
<td>0.12</td>
</tr>
<tr>
<td>6.</td>
<td>Radius of gyration (mm)</td>
<td>Normal</td>
<td>37.12</td>
<td>1.86</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Analysis of the column: When the column is considered as short, the axial stress is given by the expression

$$\sigma = \frac{P}{A} \quad (6)$$

Where P is the load supported by the cross sectional area A. For long columns, the equation given by Euler is

$$P = \frac{n^2 E I}{l^2} \quad (7)$$

Where P is the maximum critical load, E is the elastic modulus and I the moment of Inertia.

RESULTS AND DISCUSSION

Results of Reliability Using a Fortran-Based First Order Reliability Method Program for Both the Solid and I-Section Column. When putting to consideration the design dimension- (150 x 150mm) for the I and
solid section subjected to similar load ranging from 75kN to 350kN, it was observed that the solid section possesses a higher safety index than the ‘I’- section by more than 3.0 and from a load of 200kN and above, the I- section begins to tend to failure. This is indicated by the probability of failure gotten from the analysis-at 200kN, its $P_f=0.386$. At 250kN, a $P_f$ value of 0.860; at 300kN the probability of failure is 0.986 and at 350kN, the probability of failure is 0.999. This is possibly traceable to the cross sectional area provided. The I-section can safely support a maximum load of 150kN at a probability of failure of 0.02. The solid section can safely support as much as 300kN, which is actually twice as much as the I-section of similar cross-section can support at a probability of failure of 0.103.

Figure 4 shows the relationship of the safety index with varied column depths for a constant breadth of 100mm to support the design load of 260kN. The safety index-column depth relation shown in the figure 4 above depicts the performance of the two different section geometries: the solid and I-section under the design axial load of 260kN and a constant breadth of 100mm. It can be deduced that the I-section can safely support this load with a minimum depth of 400mm (that is a 100 x 400mm section) at a probability of failure of $1.22 \times 10^{-2}$. It is noteworthy that the I-section can with a depth of 350mm perform for serviceability purpose since it has a safety index of 1.149 and a corresponding probability of failure value of $7.8 \times 10^{-2}$ but, the negative safety indices show unsafe margins for the depth.

The solid section can support the design load with a minimum depth of 200mm (that is a 100 x 200mm section), actually half the size of the I-section at a probability of failure of $7.76 \times 10^{-2}$. Taking into cognizance a design load of 500kN with a constant column breadth of 150mm, it can be observed that the I-section would not safely bear this load even with a depth of 400mm (that is, a 150 x 400mm section). This is because it has a safety index value less than 1.0 which is indicative of an unsafe and inadequate section (with $P_f = 0.247$) both at serviceability and ultimate limit state except there is an increment in the depth. The solid section can on the other hand support this design load with a minimum depth of 300mm (that is, a 150 x 300mm section) or less at a probability of failure of $8.85 \times 10^{-2}$.  

Figure 3 shows the relationship between the safety index and column length under the Euler loading condition for the solid and I-section. The graph shows a very safe maximum column height of up to 4.0m for the solid section. The I-section is capable of sustaining its Euler load to a safe maximum length of 7.0m with a probability of failure of $1.97 \times 10^{-4}$. It can be deduced that the ‘I’-section depicts a higher safety index at longer lengths than the solid section. This invariably translates to the suitability of the I-section for longer columns than the solid column. This is apparently owing to its greater radius of gyration than the solid section.
Considering the whole scenario when a load of 1000kN is supported by both sections of breadth 200mm and increasing values of the depths, it can be shown and established that there is an increasing departure between the compressive capacity of the solid and I section of similar dimension. The I section was observed to still be inadequate even with its maximum section of (200 x 600mm) with a probability of failure of 0.247.

Conclusion: From a panoramic consideration of the reliability-based design carried out for the solid and I-section column of the African birch timber, the following deductions can be made. (1) In view of the design section (150 x 150mm) provided, the solid section possesses a compressive capacity that is twice as much as that of the I-section. The I-section was therefore not found adequate and suitable for the design load considering the safety index and probability of failure gotten from the reliability analysis. (2) An identified minimum depth of 400mm (that is 100 x 400mm section) was found adequate since the provided dimension (150 x 150mm) for the I-section is unsafe to bear the design load. This capacity was found to correspond to a minimum depth of 200mm (that is 200 x 100mm section) of the solid section which is practically half the dimension of the I-section. This further accentuates the fact that the solid section has a capacity twice that of the I-section of equal dimension. However, if the minimum dimension of the of the two sections capable of supporting the design load is of interest, the I-section is considered more economical than the solid section since it offers a less effective area of 11,200mm² compared to the solid section with an effective area of 20,000mm². (3) The I-section has shown a higher capacity to bear the Euler load with greater lengths than the solid section because of its greater radius of gyration and rigidity value and would be rather considered preferable for long columns than the solid section. (4) When considering the limited availability of large dimensions of solid sections, the built-up I-section would be more relevant where large sized sections are required.

REFERENCES


