Delayed Collapse of Wooden Folding Stairs

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Abstract. During operation of folding stairs, a fastener joining the ladder hanger with the frame was torn off. A person using the stairs sustained serious injury. In several dozen other locations similar accidents were observed. As a result of inspections, some threaded parts of the screws were found in the gaps between the wooden elements of the stairs’ flaps. In the construction a hatch made of wooden strips is attached to an external frame by means of metal hangers. Laboratory strength tests were conducted on three samples made of wooden elements identical to the ones used in the damaged stairs. Due to complex load distribution mechanism acting on the base of the structure, a three-dimensional FEM model was created. An original software was used for calculations. Five computational model variants were considered. As a result of the numerical analyses, it was unquestionably shown that faulty connections were the cause of the destruction of the stairs. The weakest link in the load transmission chain were found to have been the screws connecting the hatch board with the hangers.

1. Introduction

In the design and construction process of wooden structures, particular attention should be paid to the quality of joining elements that work together to secure safe transfer of applied loads. In the case of wooden structures made of small cross section profiles, in the past tongue-and-groove joints were used [1]. Currently they are commonly replaced or additionally supplemented by modern solutions in the form screws or bolts together with steel plates [2]. Durability of these joints is dependent on the conditions in which the construction is used. An important role here is also played by actual maintenance of the structure and making any necessary repairs and reinforcements.

During the operation of folding stairs, the fastener joining the steel ladder hanger with the frame made of wood and wood-based materials was torn off. As a result, a person using the stairs sustained serious injuries. In several dozen other locations similar accidents resulting in different consequences for users were observed.

As a result of visual inspection conducted in situ joining screws were identified. The threaded parts of the screws were found in the gaps between the wooden elements of the folding stairs.

2. Stairs structure

The folding stairs consist of a three-segment ladder folded alternatively. The bottom ladder segment is supported by the floor while the top segment is fixed at four points to the flap. The flap made of a wooden frame upholstered by an HDF-board is attached to an external wooden frame by means of metal hangers. The hangers have a hinged foldable structure owing to the folding mechanism of the stairs. The
hangers are mounted to the flap frame with eight screws of ø5.8/25mm, two in each of the four elements made of steel angle bars.

In the studied case, a person weighing about 100 kg (1.0 kN) used the folding stairs during the renovation of a loft in an apartment building. In the five months’ time, the man moved up and down the stairs a dozen times a day. On the day when the accident occurred, the man was trying to carry two bags of cement weighing 50 kg (0.5 kN) up the stairs. The load acting on the top step caused a disruption of the screws joining the hinges with the flap. The user confirmed that he used to transfer similar load a number of times during the renovation. At the time of breaking, the lower stair segment rested on felt pad.

3. Laboratory tests and investigations

All the damaged parts of the folding stairs were examined visually very thoroughly. The stairs were made of pine wood. It was found that the whole zones where the screws joining the upper hinges (#1, #2, #3, #4) had been located, were haphazardly disrupted. The damage may have been due to ladder breakdown, but it was impossible to exclude a hypothesis that directly before the breakage some of the screws were not fully tightened to steel elements. This assumption could be confirmed by intensive faultless use of the stairs for several months before the accident.

In order to assess the actual destructive forces operating in the disrupted joint, a series of laboratory tests [3, 4], involving axial drawing of a sample screw ø 5.8/25 mm were performed. For this purpose,
a universal strength testing machine with a capacity of 100 kN was used. Laboratory strength tests were conducted on three kinds of samples made of wooden elements corresponding to the ones used in the damaged stairs. The samples of the first kind were made in a correct way, the second one with a 4 mm gap (as in the damaged stairs) between the joined strips, and the samples of the third kind were prepared with an 8 mm gap. Figure 2 presents samples prepared for the strength tests, whereas figure 3 shows a view of the loaded and then damaged samples.

![Figure 3. View of the loaded samples in the testing machine – capacity 100kN](image)

The test results corresponded to the characteristic values of the forces calculated on the basis of the guidelines laid down in the [5], as well as according to the parameters specified by the manufacturer.

4. FEM analysis

Due to complex load distribution mechanism acting on the base of the structure whose outer frame is fixed in the ceiling level, a three-dimensional FEM model was created [6]. The model including the connections and discretization grid is illustrated in figure 4. It was as close as possible to the real structure. The stair ladder and the flap frame were described using flat four-node elements working in the membrane-plate state (planar finite slab-disc elements).

![Figure 4. One-way hinge model and top connector](image)

Between each of the three ladder segments of the stairs, at their folding points, unidirectional joints were used (figure 4a). The joint was constructed using a spring of non-linear stiffness characteristics (figure 4b). The fasteners and metal hangers between the ladder and the flap panel were modelled using three-dimensional beam elements with bi-directional joints at points corresponding to bi-directional hinges. The upper hanger is a complex element joined with a metal square bar 30x30mm. The bar, in turn, is joined to the flap frame with two screws ø 5.8/25mm. The screws were also modelled using three-dimensional beam elements (figure 4c).
5. Numerical calculation’s results

Four computational model variants were considered. They differed in the place of load and support conditions at the bottom part of the ladder stairs. The highest step of the stairs was loaded with a total force of 1500N in the middle of the step span (Variant I and III), as well as its edge (Variant II and IV). The lower part of the ladder was modelled as a supported articulated non-displaceable unit (Variant I and II) or as an articulated displaceable one (Variant III and IV). Additionally, a fifth model was taken into account. It was loaded on the edge of the step and the articulated displaceable support in the lower part, assuming zero carrying capacity of the screws (#1, #3) found in the gaps. The dead weight of the structure was routinely included in the computational program.

Figure 5. Exemplary results of the numerical computation – variant I

Figure 6. The values of the internal forces in the hangers and screws joining the hangers to the flap [kN] – Variant I: a) axial forces \( N_x \), b) transverse forces \( T_y \), c) transverse forces \( T_z \)
6. Calculations results according to standards’ requirements

The manufacturer of the stairs made the calculations according to the local standard [7] for the year 1981, assuming that each of the eight screws was subjected to the same force. The calculated characteristic bearing capacity value of a single screw was merely 250N and for eight screws the value resulted in 2.0 kN, which should ensure safe transfer of the active load even if factored values were considered. The load bearing capacity of a screw located in the gap between the framework elements of the flap was calculated as equal to 123N and the total capacity of eight screws was equal to 1.746 kN, which was sufficient to meet the standard condition.

Using the guidelines for the national standards [8], load carrying capacity of a single screw subjected to the pulling force was calculated on the basis of the following expression (the notations are given in the norm [8]):

\[ R_k = f_{5,k} (l_{ef} - d), \]  

Figure 7. The values of the internal forces in the hangers and screws joining the hangers to the flap [kN] – Variant V: a) axial forces \( N_x \), b) transverse forces \( T_y \), c) transverse forces \( T_z \)

Figure 8. The values of the internal bending moments in the stair’s steps [kN] – Variant I and V
where
\[ f_{3,k} = (1.5 + 0.6d)\sqrt{\rho_k} = (1.5 + 0.6 \cdot 3.5)\sqrt{320} = 64.4N/mm \quad (2) \]

Table 1. Results of numerical computations - the internal forces in the screws

| Variant   | Nx [N] | Ty [N] | Tz [N] |
|-----------|-------|-------|-------|
| #1        | 58    | 219   | 126   |
| #2        | 100   | 126   | 100   |
| #3        | 2019  | 126   | 0     |
| #4        | 126   | 0     | 41    |
|           |       |       | 41    |
| Variant II| 86    | 321   | 112   |
|           | 30    | 112   | 90    |
|           | 269   | 2     | 0     |
|           | 64    | 0     | 42    |
|           | 2     | 0     | 39    |
| Variant III| 94   | 103   | 327   |
|           | 103   | 210   | 210   |
|           | 94    | 327   | 0     |
|           | 103   | 210   | 0     |
|           |       | 0     | 85    |
|           |       |       | 85    |
| Variant IV| 124   | 169   | 37    |
|           | 37    | 535   | 156   |
|           | 2     | 100   | 228   |
|           | 0     | 71    | 0     |
|           | 0     | 0     | 99    |
| Variant V | 0     | 291   | 103   |
|           | 0     | 0     | 679   |
|           |       |       | 0     |
|           |       |       | 0     |
|           |       |       | 396   |
|           |       |       | 0     |
|           |       |       | 100   |

The pulling force for a screw correctly placed in wooden frame elements is \( R_{k,1} = 1,049N \), and for a screw in the gap just \( R_{k,2} = 111N \). A comparison of the calculated limit values with the values resulting from the analytical calculations (table 1) do not justify the occurrence of collapse in any of the five analyzed variants.

Making use of the guidelines for the EC norms [5], the characteristic load bearing capacity of a single screw subjected to the pulling force is calculated on the basis of the following expression (the notations are given in the norm [5]):

\[ F_{ax,k,Rk} = \frac{n_{ef} f_{ax,k} d_{ef} k_d}{1.2 \cos^2 \alpha + \sin^2 \alpha}, \quad (3) \]

where \( f_{ax,k} = 0.52d^{-0.5} l_{ef}^{-0.1} \rho_k^{0.8} \).

For a screw correctly placed in wooden frame elements \( f_{ax,k} = 16.17N \), and the pulling force equals to \( F_{ax,k,Rk} = 1,346.4N \). For a screw located in the gap \( f_{ax,k} = 18.56N/mm^2 \), and the pulling force is \( F_{ax,k,Rk} = 390.2N \).

Also, as a result of the analysis of the procedures specified in the European norm, a comparison of the calculated limit values with the values resulting from the analytical calculations (table 1) do not justify the collapse in any of the five analyzed options.

Therefore, a destruction mechanism resulting from exceeding the contact stresses should have been verified. The standard [5] requires that for the pine wood class C18 the following condition must be fulfilled:

\[ \sigma_{c,90,k} = \frac{F_{c,90,k}}{A_{ef}} \leq k_{c,90} f_{c,90,k} = 48MPa \quad (5) \]

As a result of the calculations concerning the faulty screw #1 (Variant IV), it was found that the contact stresses exceed the limit values more than twofold:

\[ \sigma_{c,90,k} = \frac{535N}{5.95mm^2} = 11.26MPa \gg k_{c,90} f_{c,90,k} = 4.8MPa. \]
The effect of the destruction of the contact zone was extraction of screws #1 and #3, after which the structure attained the state described as Variant V. The contact stresses for screw #2 also exceeded specific limit values:

\[ \sigma_{c,90,k} = \frac{679N}{14.95mm^2} = 5.11MPa > k_{c,90}f_{c,90,k} = 4.8MPa, \]

resulting in pulling out subsequent screws joining the flap with the ceiling construction.

As an effect of the numerical analyses of the computational mode, it has been shown that faulty connections could have resulted in the destruction of the stairs in three (III, IV, V) of the five calculated variants. In this cases, the felt underlay made it possible to displace the lower ladder’s element.

7. Results
The destruction of the connection of the stair plate with the steel hanger was initiated by the damage of the pressure zone connectors located in the gaps (force T_y, screw #1 and #3), which resulted in its disruption by force N_x. The absence of the connector caused a disruption of the adjacent connector, which in turn resulted in a domino effect leading to the destruction of the whole structure by breaking out all the other connectors.

As a result of the investigations, numerical computations and analyses of the fulfilment of limit states defined in the EC [5], it was found that:
- the defect was difficult to identify in the normal production process,
- correctly made connector elements work within the limits of their effort norms,
- the effort state of the elements of the stairs will be further increased when used by persons weighing more than 1000N (100kg), or jumping from the ladder steps [9],
- the insertion of a felt pad under the bottom segment of the ladder has a significant effect on the strength of internal forces in the screws fastening the hinges to the flap.

8. Discussion and conclusions
The weakest link in the load transmission chain were found to have been the screws connecting the flap board with the metal hangers. According to the criteria set out in the EC standard, as well as the national standards, the load bearing capacity of the screws placed in the gaps must be assumed to be equal to zero. However, under extreme conditions, which is the phase of structure destruction, each individual factor has its share, and, as a result, the load bearing capacity of the screw placed in the gap should have been partially taken into account.

Wooden elements of small profiles joined with screws should be continuously monitored, and any identified signs of loosening or reduction of contact force must be immediately eliminated by tightening the screws or replacing the existing ones with new screws of increased diameter, fitted to the thickness of the connected elements.

As a result of the research and calculations, the authors have formulated several recommendations for the manufacturer:
- effective and yet economical method of increasing the safety factor of the produced stairs is the use of an additional (third) screw in each of the four connections,
- to enhance the safety and durability of the stairs, it is highly recommended to replace screws with bolts where possible,
- installation and user’s manual should include the description of the conditions limiting the stairs’ capacity,
- the wooden parts of the stairs have to be protected against danger of fire [10].
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