

STATIC NUMERIC AND EXPERIMENTAL ANALYSIS OF
PREFABRICATED WINDER WOODEN STAIRCASE WITH
CENTRAL STRINGER MADE FROM SCOTS PINE
(*PINUS SYLVESTRIS L.*)

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ABSTRACT

The article describes behaviour of the structure of a prefabricated winder wooden staircase with central stringer on the material basis of Scots pine (*Pinus sylvestris L.*). It focuses on static behaviour of this structure. An analysis was performed with the use of 3D numerical modelling with the finite element method using ANSYS calculation system. The numerical analysis with an orthotropic material model and Hoffman and Tsai-Wu interactive failure criteria showed critical points of this type of analysed staircase. Subsequently, selected critical points were experimentally tested for static loading on models of wooden fragments of the staircase in the scale of 1:1. Experimental tests and numerical analyses pointed out the importance of a suitable choice of a material model of wood and the necessity to pay particular attention to designing of these points. The results and conclusions could be helpful for designing of a prefabricated winder wooden staircase with the central stringer.

KEYWORDS: Static analysis, prefabricated staircase, numerical modelling, experimental testing, central stringer, Scots pine (*Pinus sylvestris L.*).

INTRODUCTION

Wooden staircases currently designed for family houses are often dominant structures of the whole house and in many cases they complement its architecture features and help to create its internal elegant, original and unique style (Karre 2005). When designing a staircase, it is necessary to set correct dimensions of the staircase area, staircase construction system, staircase

shape and dimensions and shape of stairs, as described by Veselý and Mikš (2010), in order to comply with standards requirements, i.e. ČSN 73 4130 (2010), in the Czech Republic. The design of a staircase needs to bring into accord the static, architecture and other requirements as well as comfort of use.

The construction system of a staircase is selected on the basis of static requirements. The designed supporting structure must be stable in accordance with standard requirements and must be able to distribute all loading defined in the corresponding national standards.

One of the staircase types that meets these requirements while at the same time becoming a dominant architecture element is a prefabricated wooden staircase in different construction arrangement. The group of these staircases includes prefabricated staircases with one-sided suspended stairs with or without a stringer. Numeric analyses and experimental tests including subsequent modification of the staircase structure with one-sided suspended stairs without stringer are described in Pěňčík et al. (2015). Pěňčík (2015) deals with a detail of support of stairs of this type of staircase. Furthermore, this group includes a prefabricated spiral staircase with or without stringer. This type of staircase was numerically and experimentally tested by Pousette (2003). In addition, Pousette (2006) deals with the testing and modelling of the behaviour of wooden stairs and stair joints for prefabricated stringer staircases with two outside straight stringers (Fig. 1a,b). Another special type of prefabricated stringer staircases is a staircase with a central stringer, where the stairs are supported by a stringer or by another way, e.g. a pair of diagonal steel struts. In the majority of cases this type of staircases is designed with a straight stringer. This article deals with a description, numeric, static and experimental analysis of a special ground plan arrangement, where prefabricated stringer staircase with a central winder stringer (Figs. 2, 6) is used to overcome different height levels.

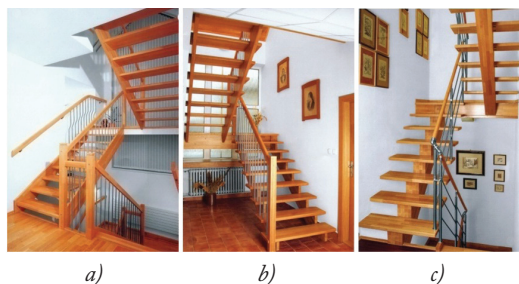


Fig. 1: Wooden prefabricated staircase with two outside straight stringers a), b) and wooden prefabricated staircase with a central straight stringer c) (JEMA Svitavy 2006).

Theoretical part

The numeric analysis of a prefabricated winder wooden staircase with a central stringer was performed on a prefabricated winder staircase made from Scotch pine (*Pinus sylvestris* L.) with the construction height of 3.0 m formed by two stringers connected to the left right-angle shape at the height of 1.46 m (Fig. 2). The lower stringer made from glued wooden profile 2×0.05 m was designed with 8 stairs without risers of 0.95×0.29 m. The higher stringer made from glued wooden profile 2×0.05 m was designed with 7 stairs without risers of the same dimensions as the lower stringer. The dimensions of stairs in the whole staircase complied with the requirements of ČSN 73 4130 (2010) for residential houses. The thickness of stairs was designed to 0.04 m. The outer staircase side had stairs suspended by a system of steel bars of $\varnothing 12/2$ mm in two frames with columns and massive handrails designed to be made from glued wooden profile 0.04×0.08 m. Every stair, with the exception of the first stair and the winder stair, had 2 steel bars suspended.

Each stair was supported from the bottom by a pair of diagonal steel struts of ϕ 16 mm.

The static analysis of prefabricated staircase was performed for the loading in accordance with ČSN EN 1991-1-1 (73 0035)-2004 Eurocode 1. The static analyses used permanent load, i.e. self-weight of the staircase including the handrail and other structure elements, and live load which was considered as even or concentrated loading of stairs and even or concentrated loading of handrail including their potential combination. The load was considered in design values, which were set in accordance with point No. 6.10 of the standard ČSN EN 1990 (73 0002)-2004. Eurocode. 1.

The preliminary analysis of the prefabricated staircase and checking of this structure was performed in software IDA NEXIS 32 (2002) with the use of a 3D beam analysis model. The material behaviour of staircase elements was considered with the use of an isotropic material model. Wooden parts of the staircase were considered as wooden laminated profile S13. The checking was performed with the use of a module of software IDA NEXIS 32 (2002) in accordance with the design standard ČSN EN 1995-1-1-2006 (73 1701) Eurocode 5. The checking showed increased level of stresses at stringers in the place of their connection.

Regarding the detected increased level of stresses at stringers the detailed behaviour analysis was performed with the use of software ANSYS (2011) and 3D analysis model. The analysis model showed in (Fig. 2) was created with the use of 3D finite elements of types BEAM188, SHELL181 and SURF154, and described in detail in software ANSYS (2011a). The method of modelling of individual staircase parts was similar to the modelling of prefabricated staircases with one-sided suspended stairs described in Pěncík et al. (2015). The boundary conditions were considered based on the real support conditions.

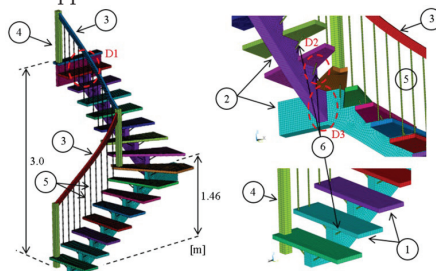


Fig. 2: 3D analysis model in software ANSYS (2011) – 1) stair, 2) stringer, 3) massive handrail, 4) column, 5) system of steel bars, 6) diagonal steel strut.

The static analysis with the use of software ANSYS (2011) in wooden staircase parts, i.e. stairs, stringers, columns and handrails, considered wood as homogeneous material, i.e. without distinguishing between the properties of early and late wood, and its behaviour was described by a rectangular orthotropy material model (Bodig and Goodman 1973) and (Bergman et al. 2010). Material properties describing this material model, see (Tab. 1), were taken from (Požgaj et al. 1997), (Matovič 1981) and (2013) and were numerically and experimentally verified in (Pěncík 2015a). The material behaviour of steel elements of the staircase was idealized by an isotropic material model. The analyses were made as materially linear and geometrically non-linear.

Tab. 1: Elastic and material constants of Scots pine (*Pinus sylvestris* L.); E , G , f [MPa], ν [-].

E_L	E_R	E_T	G_{RT}	G_{LT}	G_{LR}	ν_{RT}	ν_{LT}	ν_{LR}
14300	700	545	500	800	1230	0.38	0.04	0.03
f_{Lt}	f_{Lc}	f_{Tt}	f_{Tc}	f_{Rt}	f_{Rc}	f_{LR}	f_{LT}	f_{RT}
101.0	43.0	4.927	5.4	5.4	5.2	7.5	7.3	2.3

After the numeric analysis, the results were checked and the intensity size of stress and deformation were found. The stress was uniformly distributed in individual staircase structure parts and its average values ranged within the interval of wood strength. The stress was concentrated in the area of connections of structure parts. The use of wood material, or prediction of potential failure of wood respectively, was performed with the use of Hoffman (Hoffman 1967) and Tsai-Wu (Tsai and Wu 1971) and (Camanho 2002) failure criteria using material properties described in (Tab. 1).

The checking performed with the use of the mentioned criteria pointed out three points with increased concentration of stresses. They concerned the connection of the front board and the stringer at the last stair (D1), connection of the stair to the stringer originally provided by a pair of steel struts (D2), and a connection of winder stringers (D3). The identified points marked as (D1), (D2) and (D3) were subsequently experimentally tested and verified.

MATERIAL AND METHODS

Loading tests in the testing laboratory of the Institute of Building Testing, Faculty of Civil Engineering, VUT in Brno were performed in order to check the static behaviour of points exposed to concentrated stresses (points D1 to D3) and to find the best specific design with the aim to apply the findings for their potential changes.

The static loading was performed for all tested specimens until the full failure, in order to set their limit load bearing capacity or they were terminated for safety reasons due to excessive deflections or turning. During the testing the horizontal and vertical displacement of selected points and the force were continuously recorded with the frequency of recording of 5 Hz, i.e. in the time interval of 0.2 s, with the use of a 8-channel measuring data logger HBM SPIDER 8 (HBM 2012) connected to a PC. The horizontal and vertical displacement were monitored with the use of potentiometric sensors MS04-01 with the accuracy of 0.05 mm, with measuring range of 0 to 120.8 mm, or with the use of inductive standard displacement transducer HBH WA 20 or HBH WA 50 (HBM 2012a), with the measuring range of 0 – 20 or 0 – 50 mm and accuracy of 0.001 mm. The sensors were always placed in such way that they were independent on the loading system and that it would be possible for the evaluation to eliminate the decline of supports and other similar effects.

Test (D1)

In the test (D1) three specimens at the connection of the stringer thickness of 0.2 and height of 0.35 m with 3 cut-out segments for stairs 0.25 wide and 0.187 m high and the front board with dimensions of 1.0 × 0.34 m and thickness of 0.04 m at the initial stair were tested for loading by torsion moment. The connection of the stringer and the front board was made by 4 wood screws \varnothing 8/80 mm in combination with 4 oak dowels \varnothing 16 mm. (Fig. 3a) shows the arrangement of the test. The position of the stringer on the testing bench was secured by the pressure of 2.5 kN by a hydraulic press. Torsion moment was produced by another hydraulic press KGF U25-150, which

was fixed to the support frame in the distance of 0.4 m from the centre of the stringer, i.e. the loading was applied on the arm of 0.4 m.

The applied force was recorded by a tensometric dynamometer CSP-M-25t-C3-SC-SS put in between the hydraulic press and the upper part of the front board. All tests were terminated for safety reasons due to excessive turning of the front board.

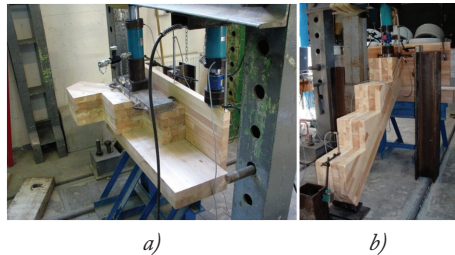


Fig. 3: Test D1: loading by torsion moment a) and shear force b).

The same connection of the stringer and the front board was also loaded by a shear force. The stringer has an inclination of 37° . The arrangement of the test is shown in (Fig. 3b).

The connection of the stringer 0.2 thick and 0.35 m high with 4 cut-out segments for stairs 0.25 wide and 0.187 m high with the front board with dimensions of 1.0×0.34 m and thickness of 0.04 m was performed in the same way as when loaded by torsion moment, i.e. the connection was made by 4 wood screws $\varnothing 8/80$ mm and 4 oak dowels $\varnothing 16$ mm. Three specimens, consisting of a part of the stringer and the front board, were mounted during the tests so that the additional board was by its bottom surface fully placed and supported on the support bench. The bottom part of the stringer was placed on a board to establish a simple support. The loading was applied by a hydraulic press KGF U25-150 which was fixed to the support frame of the testing bench in the centre of the stringer. The applied force was recorded by a tensometric dynamometer CSP-M-25t-C3-SC-SS put in between the hydraulic press and the highest edge of the stringer right at the front board, so that the bending moment was as low as possible. The tests were terminated once the failure of the connection of the stringer and the front board occurred.

Test (D2)

In the test (D2) three specimens at the connection of stairs with dimensions of 1.0×0.29 m and thickness of 0.04 m to the stringer with the inclination of 37° , thickness of 0.1 and heights of 0.2 and 0.35 m with 5 cut-out segments for stairs 0.25 wide and 0.187 m high, which were symmetrically arranged on the stringer of the total length of 2.97 m. During the tests the stair was placed on the third (middle cut-out segment for stairs) cut-out segment, as shown in the overall test arrangement in (Fig. 4).



Fig. 4: Test D2.

The bottom and top part of the stringer was placed on a board or frame to establish the simple support. During the testing the stair was placed on the upper part of the stringer and was connected to the stringer by plastic wall plugs inserted in the stringer and steel struts that were put inside of the wall plugs (Fig. 5a, b). The stair was further supported by a pair of steel struts with $\varnothing 16$ mm, which were connected to the bottom surface of the stair and side parts of the stringer with 4 wood screws $\varnothing 5/40$ mm (Fig. 5c). The loading was applied by steel loading boards of known weight, which were placed at the stair edge in the distance of 0.44 m from the stringer centre in order to reach maximum loading of the connection. The loading was performed in 9, or 10, loading steps with the intensity of loading reaching 0.36 – 0.50 – 0.61 – 0.71 – 0.82 – 0.93 – 1.04 – 1.14 – 1.45 (potentially also 1.65 kN). The testing was terminated once the failure of the connection of the stair to the stringer occurred.

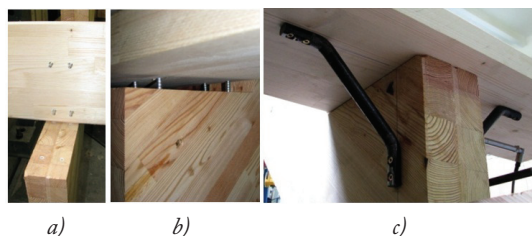


Fig. 5: Views of the connection of the stair to stringer with plastic wall plugs inserted to the stringer a) and steel struts put inside wall plugs b) and support of the stair by steel struts c).

Test (D3)

During the test (D3) three specimens of the connection of two left-turn winder stringers with the inclination of 37° , thickness of 0.1 and height of 0.35 m with segments for stairs for shear. The lower stringer consisted of 4 cut-out segments for stairs 0.25 wide and 0.187 m high, and the upper stringer consisted of 5 cut-out segments for stairs 0.25 wide and 0.187 m high. The construction height of the staircase was 1.82 m. The arrangement of the test is shown in (Fig. 6).



Fig. 6: Test D3.

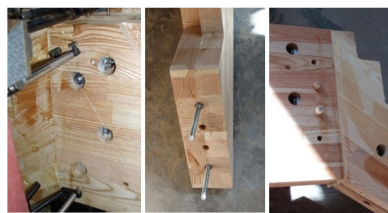


Fig. 7: View of stringers connection a), detail of connecting elements of the upper b) and bottom stringer c).

The bottom part of the stringer was placed on a board to establish the simple support. At the connection of the winder stringers the lower stringer was placed with its bottom surface on the testing bench to establish the simple support. The upper stringer was supported by frame to establish the simple support. The bottom and upper stringers were fixed together by 2 oak dowels $\varnothing 16$ mm and 2 threaded rods $\varnothing 10$ mm equipped with washers and metric screws (Fig. 7). The dowels and threaded rods were symmetrically placed from the half height of the stringer in

the distances of 0.04 and 0.1 m. The loading was applied by a hydraulic press KGF U25-150, which was fixed to the support frame of the testing bench, i.e. loading was applied on the third cut-out segment for the stair. The applied force was recorded by a tensometric dynamometer CSP-M-25t-C3-SC-SS put in between the hydraulic press and the stringer surface. The testing was terminated once the failure of the connection of stringers occurred.

RESULTS AND DISCUSSION

Test results (D1)

The failure of the stringer and front board connection at the last stair under the effects of torsion moment occurred at the use of average ultimate force 3.28 kN, which corresponds with the average torsion moment of 1.48 kNm. All three tests were terminated for safety reasons due to excessive turning of the front board. The effect of extreme force caused turning of the tested specimens of the front board up to by 5.35° to 6.12° in comparison with the initial condition. The graphic relationship between torsion displacement (rotation) and applied torsion moment is shown in (Fig. 8).

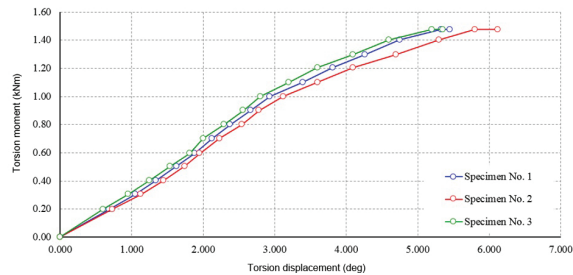


Fig. 8: Graph of relationship between torsion displacement (rotation) and applied torsion moment.

The courses also show that in the initial loading phase the linear relationship between the torsion displacement and applied torsion moment is valid. In addition, the courses show that the pushing of oak dowels \varnothing 16 mm and beginning of wood screws occurred once torsion moment reached 1.0 kNm. The view of the front stringer surface, which was in contact with the front board with partially pulled out wood screws and pushed oak dowels \varnothing 16 mm to the stringer, is shown in (Fig. 9a). The view of partially turned front board after one of the tests is shown in (Fig. 9b).

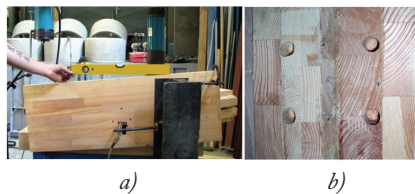


Fig. 9: View to front board a) and detail of stringer front after loading b).

During testing of the stringer and front board connection by shear a failure occurred under the use of average ultimate force of 25.12 kN (average value from 22.61 kN, 28.00 kN and 24.7 kN). All three tests were terminated for safety reasons due to overall failure of connection between the stringer and the front board. The effect of extreme force caused vertical displacement of the stringer, in comparison with the front board, on average 11.52 mm (average value from

10.76, 10.71 and 13.10 mm). The graphic relationship between stringer vertical displacement and applied force is shown in (Fig. 10).

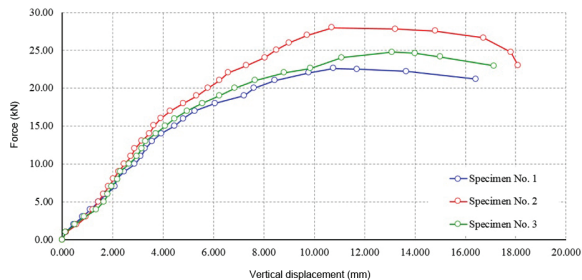


Fig. 10: Graph of relationship between vertical displacements to applied force.

The graphic relationship shows that in the initial loading phase the linear relationship between the vertical displacement and applied load is valid. Non-linear behaviour caused by gradual failure of the connection, i.e. loosening of wood screws and pushing of oak dowels \varnothing 16 mm to the stringer, or the front board respectively, is obvious once the loading reaches approx. 15 kN. The view of the failed connection with a detail of partially pulled up wood screws and pushed oak dowels \varnothing 16 mm to the stringer, or the front board respectively, is shown in (Fig. 11). One dowel was broken during one of the tests.



Fig. 11: Failed connection with a detail of partially pulled up wood screws and pushed oak dowels \varnothing 16 mm to the stringer and the front board.

Test results (D2)

In the test (D2) three specimens of connection of stair to the stringer made by a pair of steel struts and plastic wall plugs inserted in the stringer and steel dowels, which were pushed inside of the plastic wall plugs. The tests were terminated for safety reasons due to the amount of stair turning and connection opening under the loading of 1.6 kN, or the moment 0.726 kNm. Under the effect of ultimate loading, the screws \varnothing 5/40 mm, which fixed the steel struts supporting the unloaded stair part, as shown in (Fig. 12b), were torn out.

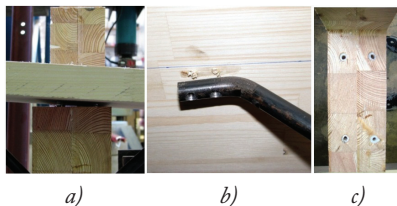


Fig. 12: View to stair and stringer connection after loading test when wood screws were torn out of the stair.

The material of inserted wall plugs was deformed (Fig. 12c). During the testing of all specimens and under the loading of 0.50 kN the connection of the stair and stringer began to split up (Fig. 12a), which is also obvious in the change of loading curve course (Fig. 13). Under the loading of 1.65 kN average vertical displacement by 24.03 mm of the loaded stair part occurred.

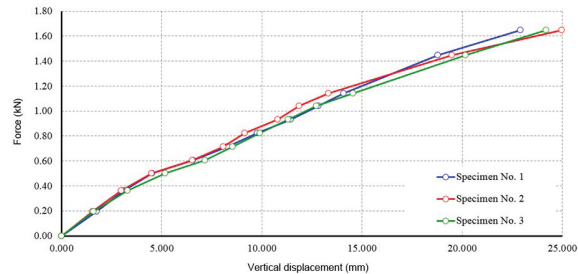


Fig. 13: Graph of relationship between vertical displacement and applied force.

Test results (D3)

In the test (D3) three specimens of connection of two left-turn winder stringers were tested. The tests of all three specimens were terminated only when the connection was fully broken, as shown in (Fig. 14).

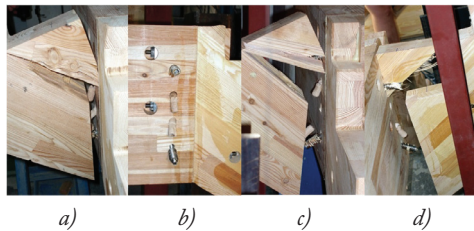


Fig. 14: View of failed stringers connection.

The upper stringer split up in the connection for all specimens. At the same time the inserted anchoring nuts to anchor threaded rods were torn out of the upper stringer. The connection failure occurred under the average force of 33.23 kN. The effect of this amount of loading caused an average displacement difference of stringers by 8.79 mm. An average vertical displacement by 6.66 mm occurred in the middle of the upper stringer.

The graphic relationship between the differences of vertical displacement of stringers in the stringers connection to the applied force is shown in (Fig. 15). The dependence courses show the linear dependence in the initial phase between the amount of applied load and the difference in stringers vertical displacement in the stringers connection. Once the initial connection failed under the loading of approx. 10 kN, the dependence became non-linear (Fig. 15).

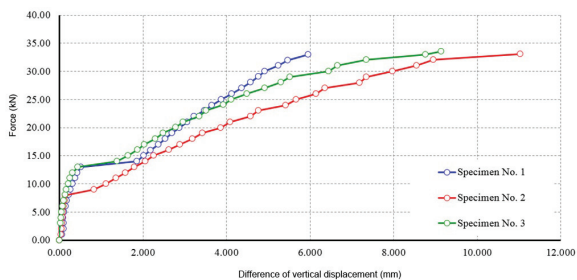


Fig. 15: Graph of relationship between differences of vertical displacements of stringers in the stringers connection to applied force.

Numeric analyses and experimental tests of the winder staircase with the central stringer pointed out the importance of selecting suitable wood material model in combination with criteria which are used for predicting material failure. The numerically determined results showed the suitability and necessity to idealize the construction in question by the numeric static model in more detail and higher accuracy. Regarding the further detailed analysis of higher loaded spots, the necessity to use more general material models was confirmed, e.g. cylindrical anisotropic plasticity material model described by Moses and Prion (2002, 2004) and used for example by Santos and Morais (2015) for numerical investigation of mechanical behaviour of wood T-joints, by Pěňčík (2015) to analyse the support of stairs in a wooden prefabricated staircase with one-sided suspended stairs made from Scots pine (*Pinus sylvestris* L.) and by Pěňčík (2015a) formodelling of experimental tests of wooden specimens from Scots pine (*Pinus sylvestris* L. <http://i.imgur.com/0Lh5w6B.gif>).

CONCLUSIONS

The results of loading tests (D1), i.e. connection of the stringer and front board, for torsion moment, showed the need to modify this detail, since the torsion moment at the failure only reached the average value of 1.48 kNm. This value of torsion moment at the failure is insufficient, since the design value of the torsion moment reached 7 kNm, based on the static analysis results of the prefabricated winder wooden staircase with the central stringer. We need to add to this conclusion, that under typical construction arrangement of the staircase the loading of this connection is favourably influenced by the interaction with normal force, which prevents splitting the joint at the connection of the additional board and the stringer, thus increasing the resistance to failure by the growth caused by friction.

The results of the loading test (D1), when the samples of the stringer and front board connection were tested for shear, showed satisfactory values. Similarly to shear stress by torsion moment, the loading of this connection is favourably influenced by the interaction with normal force.

The loading test (D2) showed that there needs to be a change in the connection of the stair and the stringer for prototype of a prefabricated winder wooden staircase with the central stringer, since under the loading of 0.50, or the moment of 0.22 kNm respectively, a joint at the stair connection was splitting up. The fixation of the stair to the stringer with wall plugs and dowels was rather flexible and the effect of dynamic loading by walking caused gradual loss of the connection rigidity. Based on the analysis of test results (D2), modifications of the connection

of the stair to the stringer were designed and tested: a) connection of the stair to the stringer by struts and eccentrically placed self-locking bolt, b) connection of the stair to the stringer with the use of a steel anchor fixed by wood screws to the stringer, c) connection of the stair to the stringer with the use of a steel anchor fixed by wood screws to the stringer in combination with struts. The variant c) seemed to be the most effective out of all designed modification.

The loading test (D3) of the connection of the stringer in the winder staircase showed effectiveness of such connection. The average shear force at the failure reached 33.23 kN. The amount of determined average force is significantly higher than the amount of shear forces determined by a static analysis of the winder staircase, which had the design value of 3.4 kN for the most unfavourable combination of loading.

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