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1 Background and introduction

A compilation of test results on timber and glulam beams with holes are presented. The tests concern relatively small beams ($h \leq 300$ mm) with relatively large circular holes ($0.5 \leq d/h \leq 0.6$). Most test series concern beams with holes which are reinforced by either internal dowel-type reinforcement (screws) or external panel-type reinforcement (glued-on plywood).

Design equations in the Final Working Draft of Design of Reinforcement in a revised Eurocode 5 (EN 1995-1-1) Version 2018-04-24 [1] are limited in validity to hole diameter $d \leq 0.3h$ for internal dowel-type reinforcement and $d \leq 0.4h$ for external panel-type reinforcement. Test results are compared to load bearing capacities for beams with holes based on EN 1995-1-1 (EC5) and Final Working Draft EC5 (2018-04-24) to investigate if the current design approach can be applied for large circular holes ($0.5 \leq d/h \leq 0.6$), which are currently not allowed. Some comments on the considered failure modes are given in Section 2.

Test results and comparison to characteristic load bearing capacities according to EC5 and the EC5-draft are presented in section 3. The test results originate from three different experimental campaigns:

- Test have recently been carried out at the research institute RISE (formerly known as SP) and results of these tests are presented in section 3.1.
- Tests carried out at Lund University (LU) as reported in [2] are presented in section 3.2.
- Tests carried out at the Norwegian University of Science and Technology (NTNU) and reported in [2-5], are summarized in [7]. Based on that summary report [7] the tests are presented in section 3.3.

Discussion and conclusions are given in section 4.

2 Characteristic capacities according to EC5 and EC5-draft

Characteristic load bearing capacities for beams with holes based on EN 1995-1-1 (EC5) and the Final Working Draft of Design of Reinforcement in a revised Eurocode 5 Version 2018-04-24 [1] have been calculated and compared to test results. Load bearing capacities with respect to the following failure modes are considered:

F_v **Capacity with respect to shear force for beam without hole**

According to EC5 assuming k_{cr} = 1.0 and considering shear strengths f_{vk} according to EN 338 for C24 and according EN 14080 for GL28cs.

F_m **Capacity with respect to bending for beam without hole**

According to EC5 taking the beam height strength modification factor k_h into account and considering bending strengths f_{mk} according to EN 338 for C24 and according EN 14080 for GL28cs.

$F_{t,90}$ **Capacity with respect to tension perp-to-grain at the hole, without reinforcement**

According to the German National Annex to EC5.

$F_{m,hole}$ **Capacity with respect to bending at the hole**

Bending moment capacity with respect to the net cross section at the hole centre, considering the beam height strength modification factor k_h and considering bending strengths f_{mk} according to EN 338 for C24 and according EN 14080 for GL28cs.

$F_{v,hole}$ **Capacity with respect to local shear stress at hole**

Considering Eqs. (PT.1-8.69) and (PT.1-8.70) in the Final Working Draft EC5 and considering shear strengths f_{vk} according to EN 338 for C24 and according to EN 14080 for GL28cs. This failure mode is assumed to be relevant only for unreinforced holes and holes with internal dowel-type reinforcement, not for panel-type reinforcement.

F_{int} **Capacity with respect to internal reinforcement**

According to the Final Working Draft EC5 section 8.4.5.2 and design resistance of the internal dowel-type reinforcement according to Eqs. (PT.1-8.35a) and (PT.1-8.35b). Strength properties of the reinforcing screws are as specified by producers.

$F_{ext.v}$ **Capacity with respect to external reinforcement: bond-line shear**

According to the Final Working Draft EC5 section 8.4.5.2 and design resistance of the glued-on panel reinforcement according to Eqs. (PT.1-8.35a) and (PT.1-8.35d) with respect to the strength of the glue-line. Strength properties of the glue line as specified in Table PT.1-8.2.

$F_{ext.t}$ **Capacity with respect to external reinforcement: panel tension**

According to the Final Working Draft EC5 section 8.4.5.2 and design resistance of the glued-on panel reinforcement according to Eqs. (PT.1-8.35a) and (PT.1-8.35d) with respect to tensile stress in the glued-on panels. Strength properties of the panels as specified by producers.

Values for load bearing capacities given in tables and figures below are based on characteristic strength values and are given as total applied load F. For each test series, the value of the failure mode with the lowest characteristic value, i.e. the ”expected failure mode” according to EC5, is underlined.

Characteristic values of test results are calculated according to EN 14358.

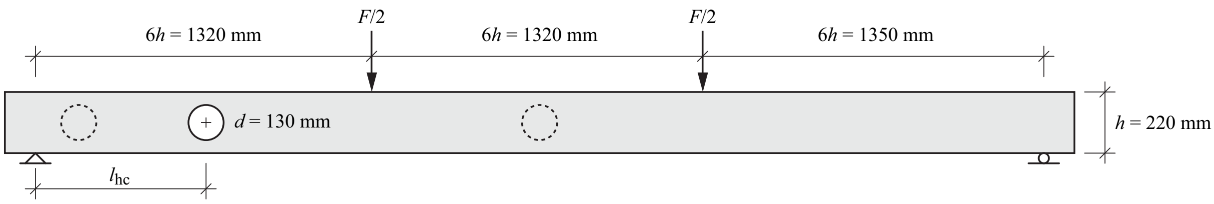
3.1 Tests from RISE

Tests on GL28cs 42×225 mm^2 and C24 45×220 mm^2 were performed using a 4-point-bending test setup according to EN 408 and a 3-point-bending test setup (denoted SHEAR) as illustrated below. Circular holes of diameter d = 130 mm were used and reference beams without holes were also tested. The number of specimens in each test series was 12 for all test series with GL28cs. For the test series with C24, 22±1 specimens were used for the EN 408 test series while 12 specimens were used for the SHEAR test series. Hole placements with respect to the distance to support and the distance to the end of the beam comply with the provisions of the Final Working Draft EC5 (2018-04-24) [1].

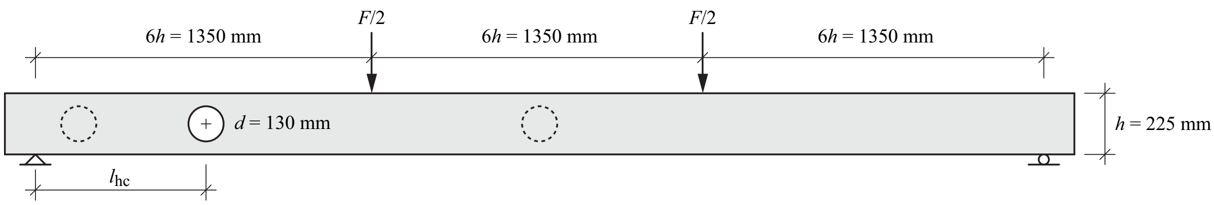
Screws SFS WT-T 6.5×220 mm and ESSVE 6.5x220 mm were used for the glulam beams with screw reinforcement. An angle α = 60° between the screw axis and the beam axis was used for hole placements with l_{hc} = 178 mm (see figures below and Tables 1-4) while α = 90° was used for the other hole placements. Characteristic capacities F_{int} given below are based on assuming α = 90° for all hole placements and are based on characteristic screw strength properties $f_{ax,k}$ = 12.9 N/mm^2 and $f_{tens,k}$ = 14.8 kN. Screw reinforcement was only used for the GL28cs beams and not for the C24 beams.

Plywood K20/70 was used as panel reinforcement for both the GL28cs beams and the C24 beams. Square panels of side length h mm were applied on both sides of the beam. The panels were glued to the beams using a polyurethane adhesive and were fixed by 12+12 wood screws 5×30 mm. A 3-ply panel of thickness t_r = 9 mm was used for the GL28cs beams. For the C24 beams used in test setups EN 408, 5-ply panels of thickness t_r = 12 mm were used. For the C24 beams used in test setup SHEAR, 3-ply panels of thickness t_r = 9 mm were used for six of the beams while 5-ply panels of thickness t_r = 12 mm were used for the remaining six beams. Characteristic capacities $F_{ext,t}$ given in the tables and figures below are based on assuming a plywood thickness t_r = 9 mm and f_{t0k} = 12 MPa.

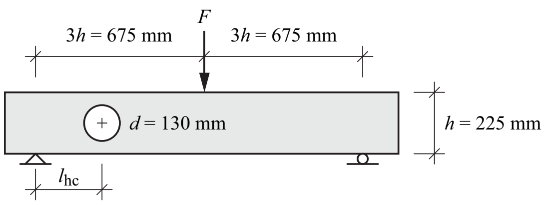
EN 408: C24 45×220 mm^2



EN 408: GL28cs 42×225 mm^2



SHEAR: GL28cs 42×225 mm^2



SHEAR: C24 45×220 mm^2

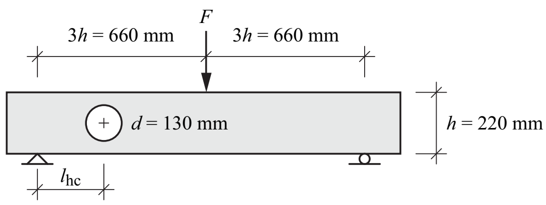


Table 1: Experimental results for GL28cs for test setup EN408 for reference beams without hole and beams with holes using screw reinforcement (LS) and plywood reinforcement (LP).

GL28cs 42×225 mm^2	Experimental results			Characteristic capacity according to EC5 and final working draft EC5							
	F_{mean}	COV	F_k	F_v	F_m	$F_{t,90}$	$F_{m,hole}$	$F_{v,hole}$	F_{int}	$F_{ext,v}$	$F_{ext.t}$
Reference	22.2	13.9%	16.5	44.1	16.2	-	-	-	-	-	-
LS l_{hc} = 178 mm	21.7	15.6%	15.7	44.1	16.2	(7.79)	72.7	10.8	26.4	-	-
LS l_{hc} = 678 mm	21.0	16.0%	14.8	44.1	16.2	(6.50)	23.7	10.8	22.0	-	-
LS l_{hc} = 2025 mm	19.5	12.3%	15.0	44.1	16.2	(14.6)	13.1	-	49.4	-	-
LP l_{hc} = 178 mm	22.7	15.1%	16.6	44.1	16.2	(7.79)	72.7	-	-	22.4	24.1
LP l_{hc} = 678 mm	21.6	17.5%	14.8	44.1	16.2	(6.50)	23.7	-	-	18.7	20.1
LP l_{hc} = 2025 mm	21.8	11.6%	17.0	44.1	16.2	(14.6)	13.1	-	-	42.0	45.1

Table 2: Experimental results for C24 for test setup EN408 for reference beams without hole and beams with holes using plywood reinforcement.

C24 45×220 mm^2	Experimental results			Characteristic capacity according to EC5 and final working draft EC5							
	F_{mean}	COV	F_k	F_v	F_m	$F_{t,90}$	$F_{m,hole}$	$F_{v,hole}$	F_{int}	$F_{ext,v}$	$F_{ext.t}$
Reference	19.8	36.1%	9.05	52.8	13.2	-	-	-	-	-	-
CP l_{hc} = 175 mm	20.1	31.6%	10.4	52.8	13.2	(6.45)	57.6	-	-	20.1	22.4
CP l_{hc} = 660 mm	20.5	28.5%	11.1	52.8	13.2	(5.38)	19.1	-	-	16.7	18.7
CP l_{hc} = 1980 mm	17.5	31.9%	8.69	52.8	13.2	(11.9)	10.5	-	-	37.1	41.4

Table 3: Experimental results for GL28cs for test setup SHEAR for reference beams without hole and beams with holes using screw reinforcement (LS) and plywood reinforcement (LP).

GL28cs 42×225 mm^2	Experimental results			Characteristic capacity according to EC5 and final working draft EC5							
	F_{mean}	*COV*	F_k	F_v	F_m	$F_{t,90}$	$F_{m,hole}$	$F_{v,hole}$	F_{int}	$F_{ext,v}$	$F_{ext.t}$
Reference	41.5	7.75%	35.4	44.1	32.3	-	-	-	-	-	-
LS l_{hc} = 273 mm	27.5	10.8%	21.9	44.1	32.3	(7.51)	52.1	10.8	25.4	-	-
LP l_{hc} = 273 mm	38.3	6.77%	33.3	44.1	32.3	(7.51)	52.1	-	-	21.6	23.2

Table 4: Experimental results for C24 for test setup SHEAR for reference beams without hole and beams with holes using plywood reinforcement.

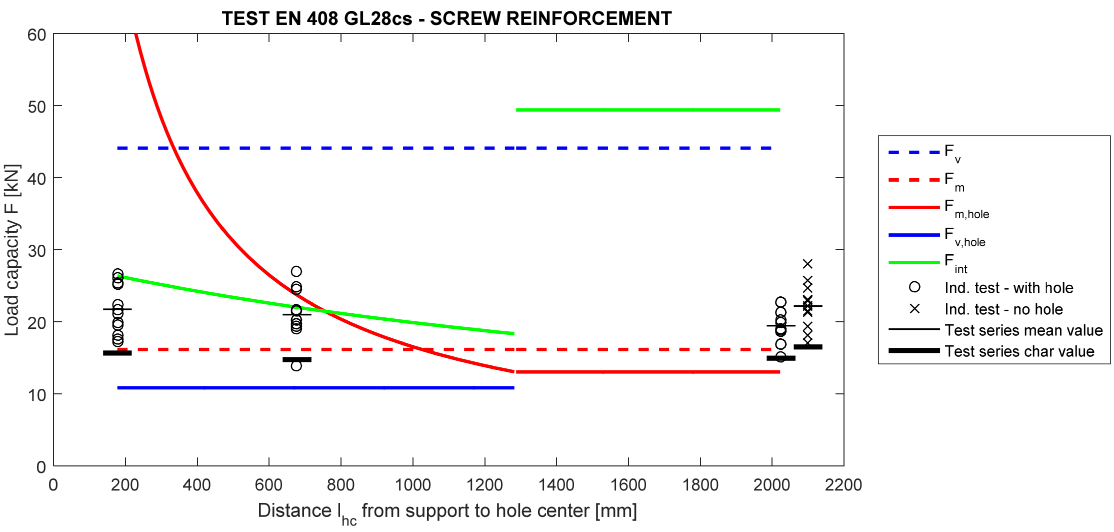
C24 45×220 mm^2	Experimental results			Characteristic capacity according to EC5 and final working draft EC5							
	F_{mean}	*COV*	F_k	F_v	F_m	$F_{t,90}$	$F_{m,hole}$	$F_{v,hole}$	F_{int}	$F_{ext,v}$	$F_{ext.t}$
Reference	36.1	14.6%	26.1	52.8	26.4	-	-	-	-	-	-
CP l_{hc} = 265 mm	30.9	22.4%	18.5	52.8	26.4	(6.22)	41.9	-	-	19.3	21.6

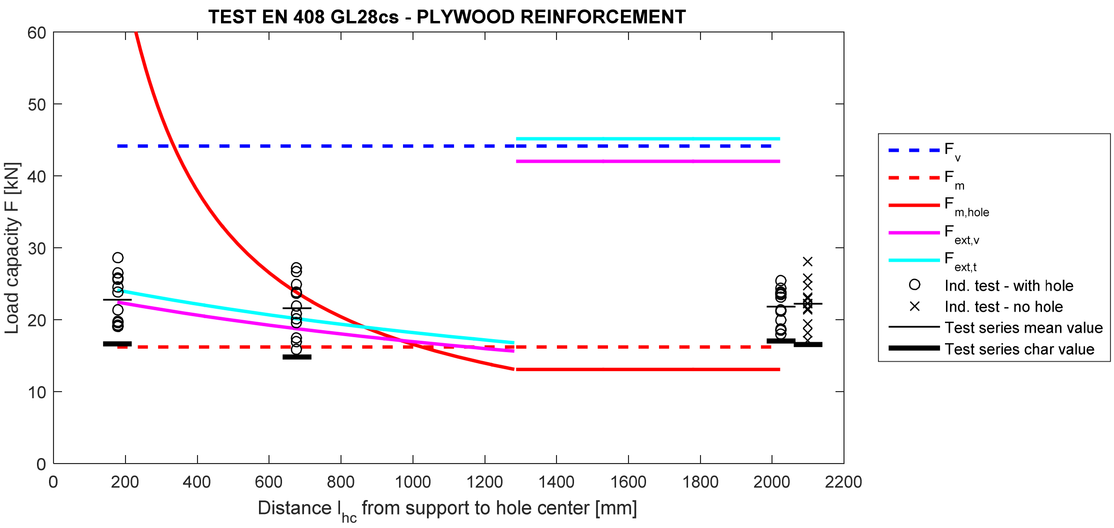
The dominating mode of failure for GL28cs using the EN 408 test setup was bending failure. Bending failures are reported for all references beams (without hole), for all beams with screw reinforcement and l_{hc} = 178 mm and for all beams with plywood reinforcement and l_{hc} = 178 and 678 mm. For the GL28cs beams with screw reinforcement and l_{hc} = 678 mm 10 specimens failed in bending, 1 specimen failed in shear at the hole and 1 specimen failed in shear but not at the hole. For hole placements in the pure bending zone, l_{hc} = 2025 mm, and screw reinforcements 8 specimens failed in bending at the hole and 4 failed in bending at other locations. For holes in the pure bending zone and plywood reinforcement 7 specimens failed in bending at the hole and 5 failed in bending in the vicinity of the hole.

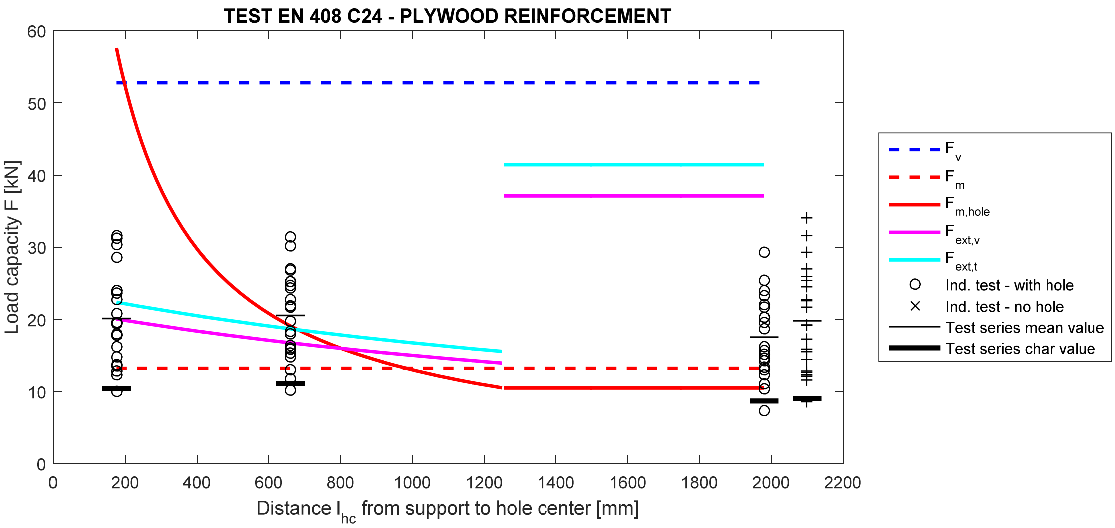
The dominating mode of failure for C24 using the EN 408 test setup was also bending. For the reference beams of C24 (without hole), 19 bending failures and 3 shear failures are reported. For the C24 beams with a hole at l_{hc} = 175mm and plywood reinforcement, 2 shear failures (one at the hole, one not at the hole) and 20 bending failures in the pure bending zone are reported. For hole placement l_{hc} = 660 mm and plywood reinforcement 3 shear failures (two at the hole, one not at the hole) and 20 bending failures are reported. For hole placement in the pure bending zone (l_{hc} = 1980 mm) 8 failures were due to bending at the hole, 2 due to shear and 11 due to bending, however not related to the hole.

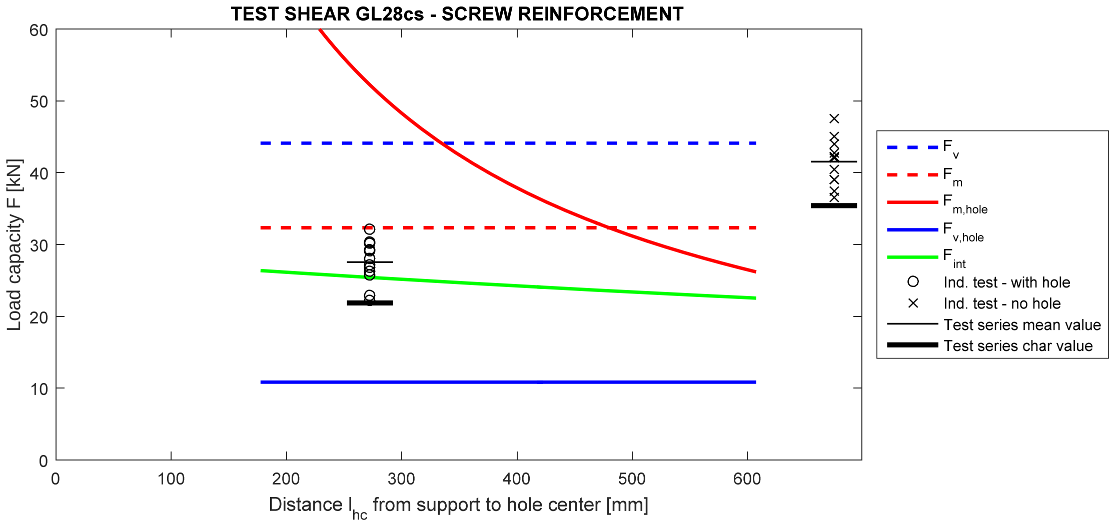
Bending failure were less frequent for the test setup SHEAR. For the GL28cs reference beams (without hole) 6 bending failures, 5 shear failures and 1 combined bending/shear failure were reported. All 12 GL28cs beams with a hole and screw reinforcement failed due to shear at the hole. For the GL28cs beams with a hole and plywood reinforcement 11 shear failures at the hole and 1 bending failure were reported.

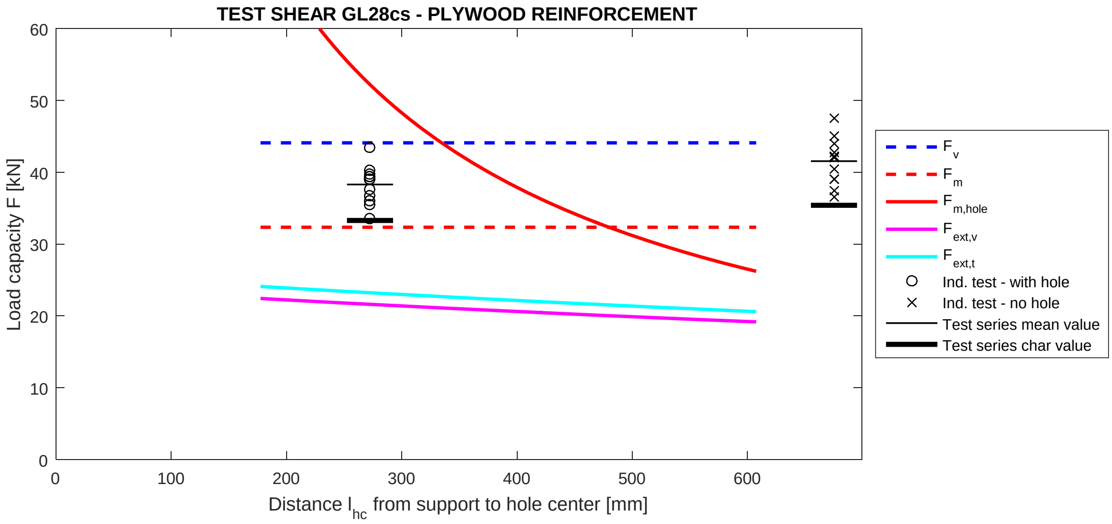
For the C24 reference beams (without hole) and using the SHEAR test setup 8 bending failures, 3 shear failures and 1 combined shear/bending failure are reported. For the C24 beams with a hole and plywood reinforcement 7 bending failures and 5 shear failures at the hole are reported.

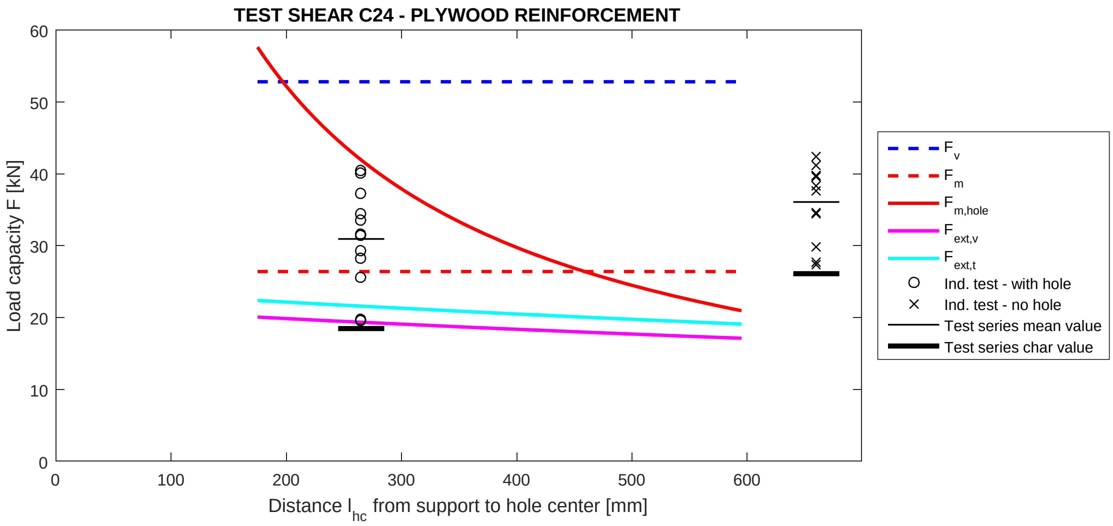

TEST EN 408 GL28cs - SCREW REINFORCEMENT
Load capacity F [kN]
Distance l_hc from support to hole center [mm]
F_v
F_m
F_m,hole
F_v,hole
F_int
Ind. test - with hole
Ind. test - no hole
Test series mean value
Test series char value


TEST EN 408 GL28cs - PLYWOOD REINFORCEMENT
Load capacity F [kN]
Distance l_hc from support to hole center [mm]
F_v
F_m
F_m,hole
F_ext,v
F_ext,t
Ind. test - with hole
Ind. test - no hole
Test series mean value
Test series char value


TEST EN 408 C24 - PLYWOOD REINFORCEMENT
Load capacity F [kN]
Distance l_hc from support to hole center [mm]
F_v
F_m
F_m,hole
F_ext,v
F_ext,t
Ind. test - with hole
Ind. test - no hole
Test series mean value
Test series char value


TEST SHEAR GL28cs - SCREW REINFORCEMENT
Load capacity F [kN]
Distance l_{hc} from support to hole center [mm]
F_v
F_m
$F_{m,hole}$
$F_{v,hole}$
F_{int}
Ind. test - with hole
Ind. test - no hole
Test series mean value
Test series char value

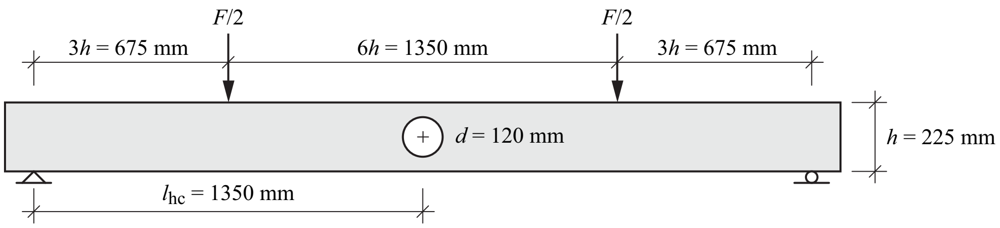

TEST SHEAR GL28cs - PLYWOOD REINFORCEMENT
Load capacity F [kN]
Distance l_{hc} from support to hole center [mm]
F_v
F_m
$F_{m,hole}$
$F_{ext,v}$
$F_{ext,t}$
Ind. test - with hole
Ind. test - no hole
Test series mean value
Test series char value


TEST SHEAR C24 - PLYWOOD REINFORCEMENT
Load capacity F [kN]
Distance l_{hc} from support to hole center [mm]
F_v
F_m
$F_{m,hole}$
$F_{ext,v}$
$F_{ext,t}$
Ind. test - with hole
Ind. test - no hole
Test series mean value
Test series char value

3.2 Tests from LU

Tests on GL28cs 42×225 mm^2 using two different test setups as illustrated below are reported in [2]. Circular holes of diameter d = 120 mm were used for all tests on beams with a hole. Reference beams without holes were also tested for each of the two test setups. Screws SFS WT-T 6.5×220 mm ($f_{ax,k}$ = 12.9 N/mm^2, $f_{tens,k}$ = 14.4 kN) and SFS WFD 8.0×220 mm ($R_{ax,k}$ = 8.72 kN), screwed at an angle of 90° to the beam axis, were used as reinforcement. The screws were positioned at distance of 40 mm from the hole edge, except for test series B3 and B4 where 20 mm was used. All test series consisted of 6 nominally equal specimens, with the exception of test series A4 where 5 specimens were used.

TEST SETUP A



TEST SETUP B

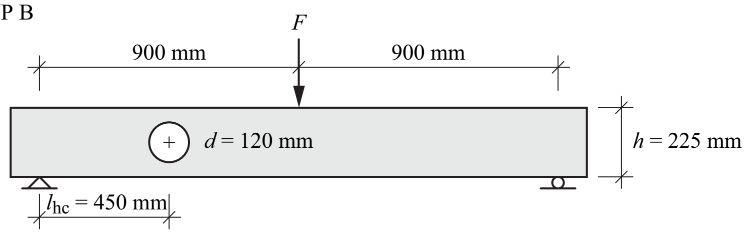


Table 5: Experimental results for GL28cs for test setup A for reference beams without hole (A1), beams with hole but without reinforcement (A2), and beams with holes and screw reinforcement (A3 and A4).

GL28cs 42×225 mm^2	Experimental results			Characteristic capacity according to EC5 and final working draft EC5					
	F_{mean}	COV	F_k	F_v	F_m	$F_{t,90}$	$F_{m,hole}$	$F_{v,hole}$	F_{int}
A1: Reference	36.7	26.3%	18.6	44.1	32.3	-	-	-	-
A2: hole, no reinf.	33.8	10.2%	26.6	44.1	32.3	31.5	27.4	-	-
A3: hole, WT-T	33.9	23.6%	16.5	44.1	32.3	(31.5)	27.4	-	115
A4: hole, WFD	35.2	11.5%	26.7	44.1	32.3	(31.5)	27.4	-	98.9

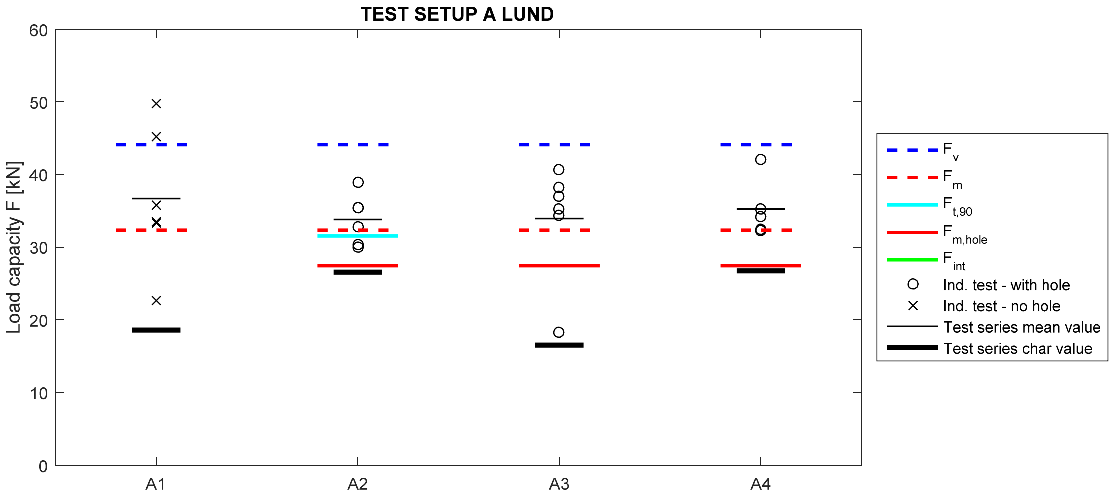
Table 6: Experimental results for GL28cs for test setup B for reference beams without hole (B1), beams with hole but without reinforcement (B2) and beams with holes and screw reinforcement (B3, B4 and B5).

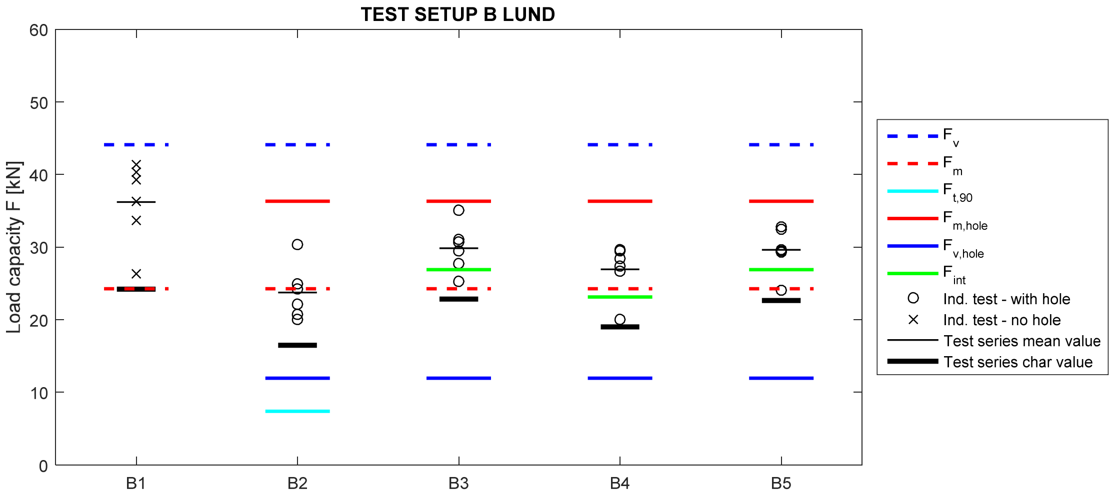
GL28cs 42×225 mm^2	Experimental results			Characteristic capacity according to EC5 and final working draft EC5					
	F_{mean}	COV	F_k	F_v	F_m	$F_{t,90}$	$F_{m,hole}$	$F_{v,hole}$	F_{int}
B1: Reference	36.2	15.3%	24.2	44.1	24.3	-	-	-	-
B2: hole, no reinf.	23.7	15.9%	16.5	44.1	24.3	7.38	36.3	11.9	-
B3: hole, WT-T *	29.8	11.2%	22.8	44.1	24.3	(7.38)	36.3	11.9	26.9
B4: hole, WFD *	26.9	13.1%	19.0	44.1	24.3	(7.38)	36.3	11.9	23.1
B3: hole, WT-T	29.6	10.7%	22.6	44.1	24.3	(7.38)	36.3	11.9	26.9

* screw distance 20 mm

For test setup A (test series A1, A2, A3 and A4) all failures are reported as due to bending. For the test series of beams with a hole (A2, A3 and A4), no clear statements on whether the bending failures are initiated at the holes or not are given in [2].

For test series B1 (without a hole), beams are reported as failed due to bending. The failure modes for test series B2 are reported as 5 shear failures at the hole and 1 bending failure, for test series B3 as 3 shear failures at the hole, 1 shear failure and 2 bending failures while all beams for test series B4 and B5 are reported as shear failures at the hole.





3.2 Tests from NTNU

Tests on glulam beams denoted as “K-bjelke” and “S-bjelke” using three different test setups as illustrated below are reported in [3-6] and results are compiled in [7]. A total of 22 test series are reported with a total of 232 individual tests. Details about the test series are given in Table 7.

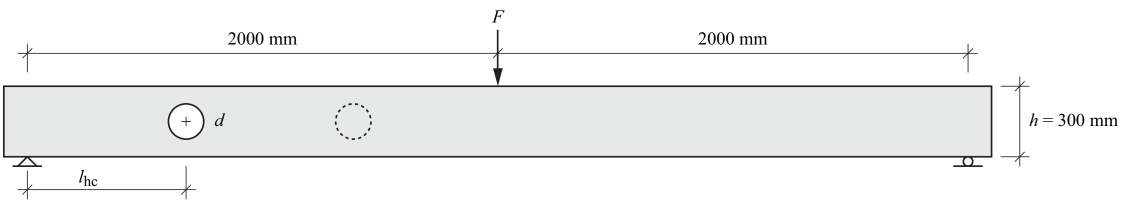
The beam height was consistently h = 300 mm and circular holes of diameter d = 150, 160 and 170 mm were tested. Reference beams without holes were also tested for two of the three test setups.

Fully threaded screws SPAX 8.0×300 mm were used as reinforcement for all beams where reinforcement was used. An angle α = 90° between the screw axis and the beam axis was used for most test series but tests were also performed with α = 30°, 45° and 60°. Characteristic capacities F_{int} given in the figures below are based on assuming an angle α = 90° for all tests and are based on characteristic screw strength properties $f_{\mathrm{ax,k}}$ = 12.0 N/mm^2 and $f_{\mathrm{tens,k}}$ = 13.0 kN.

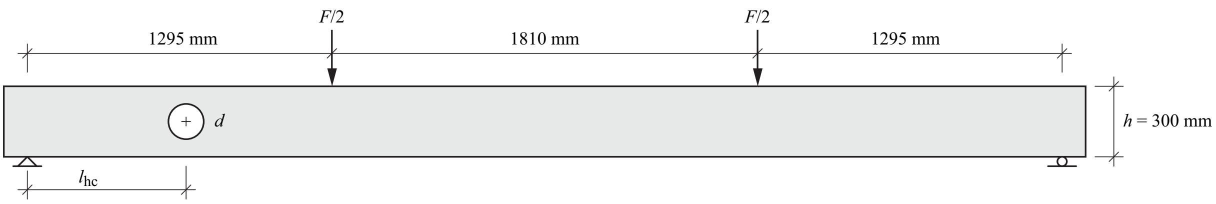
The screws were in general positioned at a distance of 2d_{r} = 16 mm from the hole edge, except for test series BMS-45-170-(0,5d) were 0.5d_{r} = 4 mm was used.

Characteristic material strength values for “K-bjelke” used for calculation of characteristic load bearing capacities according to EC5 and the EC5-draft are according to Teknisk Godkjenning SINTEF Certification Nr. 2365. The beam height modification factor for the bending strength is for “K-bjelke” assumed as k_{h} = 1.0. Characteristic material strength values for “S-bjelke” are according to glulam strength class GL28c according to EN 14080.

TEST SETUP C: K-bjelke 36×300 mm^2



TEST SETUP D: K-bjelke 48×300 mm^2, S-bjelke 48×300 mm^2



TEST SETUP E: K-bjelke 48x300 mm^2, S-bjelke 48x300 mm^2

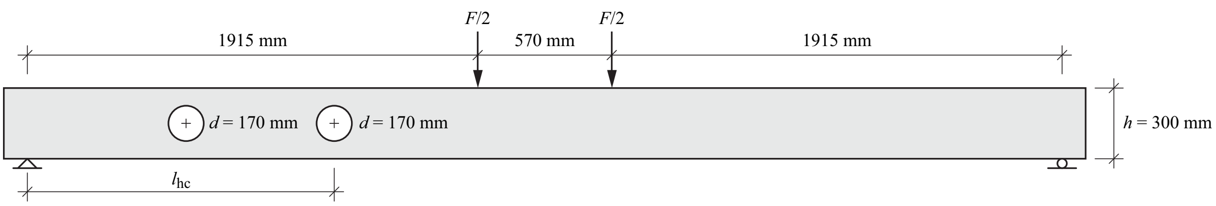
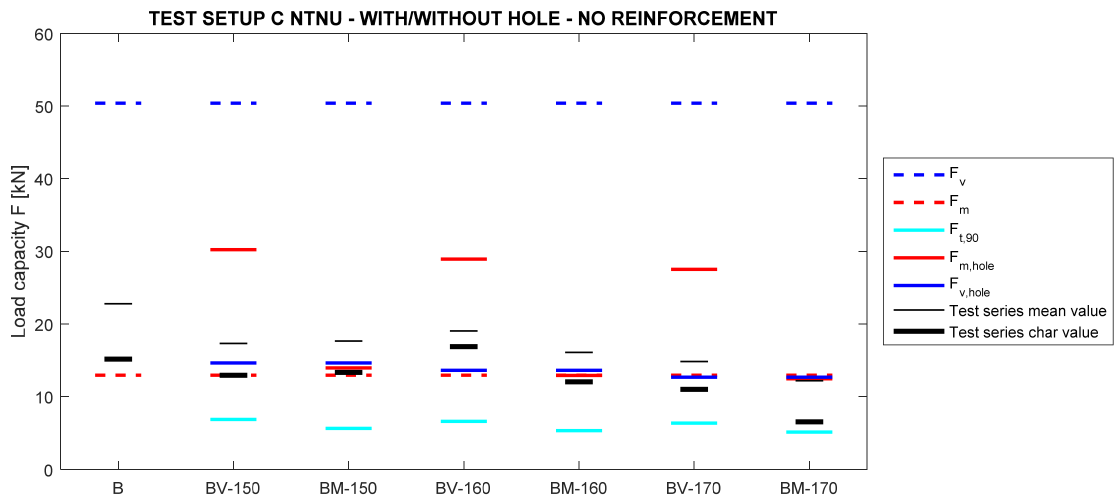
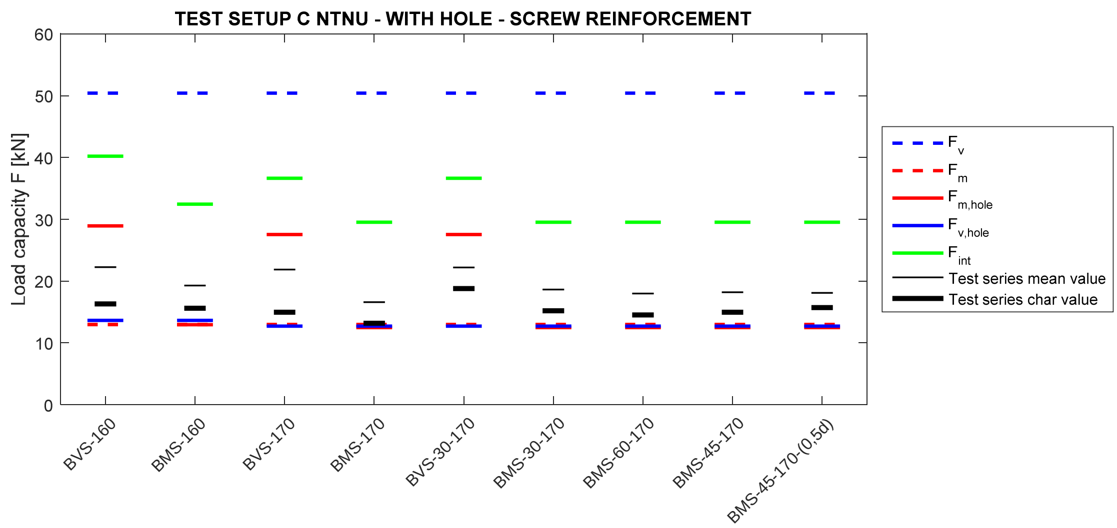
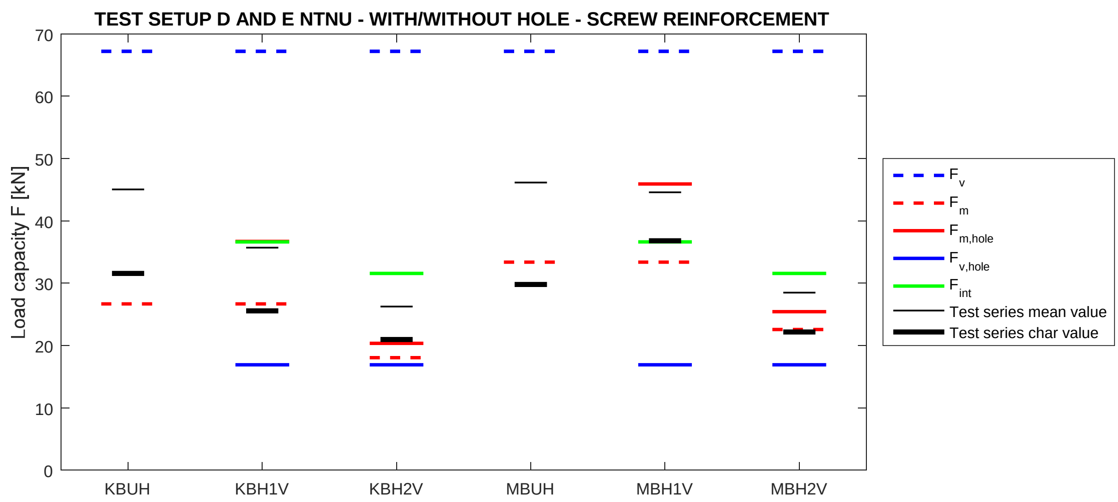


Table 7: Test series from NTNU.

Name	Test setup	n	Material	$b \times h$ [mm^2]	d [mm]	l_{hc} [mm]	$M/(Vh)$ [-]	Screw $d_r \times l_r$, α	Ref.
B	C	9	K-bjelke	36×300	-	-		-	[3]
BV-150	C	11	K-bjelke	36×300	150	675	2.50	-	[3]
BM-150	C	10	K-bjelke	36×300	150	1550	5.42	-	[3]
BV-160	C	8	K-bjelke	36×300	160	680	2.53	-	[3]
BM-160	C	10	K-bjelke	36×300	160	1620	5.67	-	[3]
BV-170	C	11	K-bjelke	36×300	170	685	2.57	-	[4]
BM-170	C	11	K-bjelke	36×300	170	1615	5.67	-	[4]
BVS-160	C	11	K-bjelke	36×300	160	680	2.53	8×300, 90	[4]
BMS-160	C	10	K-bjelke	36×300	160	1620	5.67	8×300, 90	[4]
BVS-170	C	11	K-bjelke	36×300	170	685	2.57	8×300, 90	[4]
BMS-170	C	11	K-bjelke	36×300	170	1615	5.67	8×300, 90	[4]
BVS-30-170	C	11	K-bjelke	36×300	170	685	2.57	8×300, 60	[4]
BMS-30-170	C	11	K-bjelke	36×300	170	1615	5.67	8×300, 60	[4]
BMS-60-170	C	11	K-bjelke	36×300	170	1615	5.67	8×300, 30	[4]
BMS-45-170	C	10	K-bjelke	36×300	170	1615	5.67	8×300, 45	[5]
BMS-45-170-(0,5d)	C	10	K-bjelke	36×300	170	1615	5.67	8×300, 45	[5]
KBUH	D	11	K-bjelke	48×300	-	-	-	-	[6]
KBH1V	D	11	K-bjelke	48×300	170	685	2.57	8×300, 90	[6]
KBH2V	E	11	K-bjelke	48×300	170	1305	4.63	8×300, 90	[6]
MBUH	D	11	S-bjelke	48×300	-	-	-	-	[6]
MBH1V	D	11	S-bjelke	48×300	170	685	2.57	8×300, 90	[6]
MBH2V	E	11	S-bjelke	48×300	170	1305	4.63	8×300, 90	[6]


TEST SETUP C NTNU - WITH/WITHOUT HOLE - NO REINFORCEMENT
Load capacity F [kN]
B
BV-150
BM-150
BV-160
BM-160
BV-170
BM-170
F_v
F_m
$F_{t,90}$
$F_{m,hole}$
$F_{v,hole}$
Test series mean value
Test series char value


TEST SETUP C NTNU - WITH HOLE - SCREW REINFORCEMENT
Load capacity F [kN]
BVS-160
BMS-160
BVS-170
BMS-170
BVS-30-170
BMS-30-170
BMS-60-170
BMS-45-170
BMS-45-170-(0.5d)
F_v
F_m
$F_{m,hole}$
$F_{v,hole}$
F_{int}
Test series mean value
Test series char value


TEST SETUP D AND E NTNU - WITH/WITHOUT HOLE - SCREW REINFORCEMENT
Load capacity F [kN]
KBUH
KBH1V
KBH2V
MBUH
MBH1V
MBH2V
F_v
F_m
$F_{m,hole}$
$F_{v,hole}$
F_{int}
Test series mean value
Test series char value

4 Discussion and conclusions

Some comments on the test results and predictions according to EC5 (EN 1995-1-1 and the Final Working Draft of Design of Reinforcement in a revised Eurocode 5 Version 2018-04-24 [1]) presented in Section 3 are given below.

Tests from RISE

For the test series with GL28cs using test setup EN 408, the characteristic values of the beam strength found from the tests are greater than the lowest characteristic capacity as predicted by EC5 for 6 out of the 7 test series. The exception is the test series with plywood reinforcement and hole placement l_{hc} = 678 mm where the characteristic strength of the tests reaches only 91% of the predicted EC5 characteristic strength value. For GL28cs and test setup EN408 the experimentally found failure modes are heavily dominated by bending. The difference in experimentally found beam strengths for the reference beams without a hole and for the beams with a hole placed in the pure bending zone is rather small and this agrees well with the predicted difference according to EC5 (considering the full beam cross section or a reduced cross section at the hole centre).

For the test series with GL28cs using test setup SHEAR the characteristic values of the beam strength found from the tests are greater than the lowest characteristic capacity as predicted by EC5 for both reinforcement methods used. For the beams with plywood reinforcement the experimentally found characteristic capacity is 54% greater than the capacity according to EC5 (bond-line shear). For the beams with screw reinforcement the experimentally found characteristic capacity is 103% greater than the capacity according to EC5 (local shear stress at hole). The full characteristic capacity of the screw reinforcement according to EC5 is however not reached.

All tests on C24 show lower beam strength than predictions according to EC5 on the characteristic level. However, bearing in mind the limited number of test specimens, and noting that, for example, the reference beams in the test series with C24 and plywood reinforcement using test setup EN 408 had a characteristic load bearing capacity of only 69% of the predicted one (9.05/13.2, see Table 2), it might be relevant to compare instead the relative loss of capacity based on the mean levels. Doing so, the test results of the reference beams without hole and the beams with a hole placed in the pure bending moment zone indicate (as for the GL28cs tests) that the approach in EC5 can be used to predict the bending moment capacity.

For the test series with C24 using test setup SHEAR, a very good agreement is found between the experimentally determined characteristic load bearing capacity and the EC5 predictions, however with experimentally determined values being slightly lower.

Tests from LU

For test series A, with holes placed in a zone of pure bending, the characteristic values of the test results are all lower than the corresponding characteristic strength prediction according to EC5. Considering also here, as discussed above for the C24 tests from RISE, the relatively few repetitions in each test series (5-6) and the significant scatter in results for some test series, it might be relevant to instead compare the relative loss of load bearing capacities based on mean levels. Doing so, the EC5 approach seem capable of capturing the relative loss in load bearing capacity for a beam with a hole placed in a zone of pure bending.

For test series B, the characteristic values of the beam strength found from the tests are greater than the lowest characteristic capacity of EC5 for all test series. For the beams with screw reinforcement the experimentally found characteristic capacity is 60-90% greater than the predicted capacity according to EC5 (local shear stress at hole). The full characteristic capacity of the screw reinforcement according to EC5 is however not reached for any of these three test series.

Tests from NTNU

For the tested beam types "K-bjelke" and "S-bjelke", the characteristic capacities found from tests are greater than the lowest characteristic capacity of EC5 for 21 out of the 22 test series. The exception, with experimentally determined load bearing capacity not reaching the EC5 characteristic level, is test series MBUH concerning reference beams without holes.

It should however be noted that the load bearing capacity according to EC5 for most test series is limited by bending at the hole ($F_{m,hole}$), bending of the full cross section at the location of maximum bending moment (F_m) or by local shear stress at the hole ($F_{v,hole}$) and not by the predicted capacity with respect to the screw reinforcement. The predicted capacity of the screw reinforcement is reached only for one test series (MBH1V). For the remaining 12 test series with screw reinforcement the experimentally found characteristic capacity is only about half that of the EC5-predicted capacity of the screw reinforcement (F_{int}).

References

[1] Final Working Draft of Design of Reinforcement in a revised Eurocode 5 (EN 1995-1-1), Version 2018-04-24.

[2] N. Marberg, D.G. Abdulaziz: Inverkan av större hål i klyvbalkar. Report TVBK-5203, Division of Structural Engineering, Lund University, 2012.

[3] A. Degro: The strength of glulam beams with round holes. Master's thesis, NTNU, Trondheim, 2010.

[4] P. Ø. Solberg: Selvborrede skruer som forsterking i utsparte limtrebjelker. Master's thesis, NTNU, Trondheim, 2011.

[5] K. Steen: Tøyningsendringer rundt utsparinger i limtrebjelker forsterket med selvborrende skruer. Master's thesis, Trondheim, 2012.

[6] E. Skonhovd, J. K. Tosterud: Laboratorieforsøk og numerisk analyse av limtrebjelker med store skrueforsterkede hull. Master's thesis, NTNU, Trondheim 2016

[7] K.A. Malo, A.K. Paulsrud: Store hull i bjelker av smalt limtre, S-bjelken og K-bjelken. Insitutt for konstruksjonsteknikk, NTNU, Trondheim, 2017.