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Net cross-section failure of steel plates at bolt holes

Numerical work and statistical assessment of design rules

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ABSTRACT

This paper concentrates on the design rule for net cross-section resistance as one of the design rules relevant for bolted connections. In a previous paper twelve experimental test results were presented of a test program containing 28 specimens in total, with different bolt hole configurations, ranging from one bolt hole to multiple staggered and non-staggered holes. The specimens contain bolts or not, meaning that plates with only bolt holes are tested as well as plates connected by bolts. This paper now summarizes all experimental test results.

Subsequently, these experimental test results were used to validate a finite element model. Strain hardening needs to be taken into account in the numerical model. The paper discusses the result for different strain hardening models available in codes.

The validated finite element model was then used to create a database of numerical test results. In the database, configurations of plates with and without bolts are included. Bolts M16, M20 and M24 are considered. Both staggered and non-staggered bolt configurations are included with different end and edge distances and pitches. Plate thicknesses range from 8 to 26 mm. Most configurations use steel grade S235 but S460 was also considered.

The database was used to perform a statistical assessment of the current design rule for net-section resistance, using the procedure of Annex D of EN 1990 as further developed in the RFCS project Safebrictile together with the statistical distributions for steel properties of Safebrictile.

It was found that the current partial factor is over-conservative and can be substantially lowered. Alternatively, the design rule can be modified. The paper concludes with a proposal for a new design rule.

Keywords: net cross-section, bolted connection, statistical assessment, partial factor

1 INTRODUCTION

1.1 General

Clause 6.2.3 of EN 1993-1-1 (Eurocode 3) [1] gives the design rules for cross-sections in tension. The design tension resistance is the smallest value of the design plastic resistance for the gross cross-section and the design ultimate resistance of the net cross-section at holes for fasteners. This paper concentrates on the design rule for net cross-section resistance as one of the design rules relevant for bolted connections. In a previous paper presented at the Eurosteel conference in Naples [2], twelve experimental test results were presented of a test program containing 28 specimens in total. These specimens have different bolt hole configurations, ranging from one bolt hole to multiple staggered and non-staggered holes. The specimens do contain bolts or not. In the latter case only plates with bolt holes are tested. In the meantime, all 28 specimens were tested and the results are reported in this paper [3, 4].

The experimental test results were used to validate a finite element model. Strain hardening needs to be taken into account in the numerical model. The paper discusses the result for three different strain hardening models available in codes. The model proposed in EN 1993-1-5 [5] was used for further analyses. The finite element model could be validated against the test results using this strain hardening model.

The validated finite element model was then used to create a database of numerical test results. In the database, configurations of plates with and without bolts are included. Bolts M16, M20 and M24 are considered. Both staggered and non-staggered bolt configurations are included with different end and edge distances and pitches. Plate thicknesses range from 8 to 26 mm. Most configurations use steel grade S235 but S460 was also considered.

The database was used to perform a statistical assessment to evaluate the safety level of the current design rule for net-section resistance and its associated partial factor, using the procedure of Annex D of EN 1990 as further developed in the RFCS project Safebrictile [6, 7] and with the statistical distributions for steel properties of Safebrictile.

1.2 Net cross-section failure

As stated in [2], bolt holes in the plate reduce the cross-section and if net cross-section failure is decisive, the plate starts to yield at the most governing net cross-section instead of gross cross-section yielding. Then, by increasing the load further, the net cross-section first starts to neck and finally fails.

Three different basic bolt hole configurations were investigated [2]: one single bolt hole (1), multiple transverse bolt holes (2) and staggered bolt holes (3), as shown in *Fig. 1a*. Moreover, the possible difference in failure behavior and ultimate resistance between configurations with bolts (B) and without bolts (A) was investigated as well.

Fig. 1. a) Configurations and their failure modes; b) Staggered bolted connection: end and edge distances (e_1 and e_2 respectively) and pitch in the, and perpendicular to the, direction of the load (p_1 and p_2 respectively)

1.3 Current code requirements

The text of [2] is partly repeated here for completeness. According to cl. 6.2.3 of EN 1993-1-1 [1], the design tension resistance $N_{t,Rd}$ of the plate should always be greater than the design value of the tension force N_{Ed} . The design tension resistance is the smallest value of the design ultimate resistance of the net cross-section at holes for fasteners $N_{u,Rd}$, Eq. (1), and the design plastic resistance for the gross cross-section $N_{pl,Rd}$, Eq. (2).

$$N_{u,Rd} = \frac{0.9 A_{net} f_u}{\gamma_{M2}} \quad (1)$$

$$N_{pl,Rd} = \frac{A f_y}{\gamma_{M0}} \quad (2)$$

Where A area of a cross-section with $A = bt$ [mm²]

b plate width

t plate thickness

A_{net} net-area of a cross-section [mm²]

f_u ultimate strength [N/mm²]

f_y yield strength [N/mm²]

γ_{M0} partial factor for resistance of cross-sections for every class ($\gamma_{M0} = 1,00$) [-]

γ_{M2} partial factor for resistance of cross-sections in tension to fracture ($\gamma_{M2} = 1,25$) [-]

In a bolted connection with staggered holes, the plate can fail in two different ways: transverse over one bolt hole or zigzag over multiple bolt holes, as shown in *Fig. 1b*. The net-area of a zigzag cross-section has to be calculated with the hole reduction formula based on Cochrane's theory [8], *Eq. (3)*.

$$A_{net} = A - t \left(n d_0 - \sum \frac{p_1^2}{4 \cdot p_2} \right) \quad (3)$$

Where t thickness of the plate [mm]
 n is the number of holes extending in any diagonal or zigzag line progressively across the member or part of the member [-]
 d_0 diameter of the hole [mm]
 p_1 pitch between holes in the direction of the load, see *Fig. 1b* [mm]
 p_2 pitch between holes perpendicular to the direction of the load, see *Fig. 1b* [mm]

The partial factor for tension resistance to fracture in *Eq. (1)* relates to the safety level and is a fixed value, which is statistically determined and may be defined differently by each country. Omitting this partial factor leaves the resistance function to be evaluated.

The Eurocode makes no distinction between plates with bolt holes with and without bolts being present.

1.4 Literature survey

For a brief survey of early literature [8-11] on net cross-section resistance, the reader is referred to [2]. Recently, in [12], a revised design equation for net cross-section resistance of stainless steel connections was proposed and its reliability was demonstrated by means of statistical analysis. It was shown that the reduction factor 0.9 in the net cross-section resistance formula could be removed. In [13] test results for specimens failing on their net cross-section were reported. The paper suggests that perhaps the factor 0.9 can be omitted from *Eq. (1)* if more research is done.

2 EXPERIMENTAL TEST RESULTS

2.1 Experimental program and test set-up

Experimental program and test set-up were extensively described in [2]. Only essential points necessary for understanding of the remainder of this paper are repeated here.

Steel grade S235JR with measured values of the yield strength $f_y = 283 \text{ N/mm}^2$ and tensile strength $f_u = 449 \text{ N/mm}^2$ was used in the current investigation. All specimens have similar dimensions: the nominal plate thickness is $t = 8 \text{ mm}$ and the nominal width is $b = 110 \text{ mm}$. Non-preloaded bolts M16 of grade 8.8 were used, with the required nominal hole diameter of 18 mm.

As shown in *Fig. 1a*, the experimental program consists of three bolt hole configurations: one centric bolt hole (1), multiple transverse holes (2) and staggered holes (3). All configurations were tested with bolts (B) and without bolts (A). *Fig. 2* shows the test set-up. The specimens with bolts are symmetrically loaded by two connection plates, see *Fig. 2a*. All specimens were designed to fail at the net cross-section. Therefore, the specimens with bolts (B) have additional bolt(s) at a certain

Fig. 2. a) Test set-up (schematically); b) Test set-up A-set (without bolts); c) Test set-up B-set (with bolts)

distance from the connection to prevent the specimen to fail in bearing, *Fig 2c*.

The dimensions of all 28 specimens of the full test program are presented in *Table 1*. The tests were carried out on a 400 kN test rig (*Fig.2b,c*) at a displacement rate of 1.5 mm/min.

2.2 Test results

Typical test results were reported in [2]. An overview of all experimental net-section resistances is shown in *Table 1* together with the associated theoretical resistances. $N_{u,exp}$ is the experimental resistance obtained in the test. $N_{u,th}$ is the theoretical resistance obtained with *Eq. (1)* omitting the partial factor which comes down to using $\gamma_{M2} = 1.0$. Then the ratio $N_{u,exp}/N_{u,th}$ is given.

Table 1. Geometry and the experimental/theoretical resistances of the specimens

Test	b	t	d_0	e_2	e_1	p_1	p_2	A_{net}	$N_{u,th}$	$N_{u,exp}$	$N_{u,exp}/N_{u,th}$	$N_{u,fem}$	$N_{u,fem}/N_{u,exp}$
[-]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm ²]	[kN]	[kN]	[-]	[kN]	[-]
A11	110.03	7.99	17.98	55.02	-	-	-	735	276.0	327.0	1.18	337.9	1.03
A12	110.01	7.99	17.98	55.01	-	-	-	735	276.0	328.6	1.19	337.9	1.03
A21	110.00	8.00	18.00	30.00	-	-	50.00	592	222.1	275.2	1.23	290.5	1.06
A22	110.00	8.00	18.00	30.00	-	-	50.00	592	222.1	278.9	1.25	290.5	1.03
A23	110.05	7.98	17.98	25.03	-	-	60.00	591	221.9	278.9	1.26	289.0	1.04
A24	110.10	8.00	17.98	25.05	-	-	60.00	593	222.6	280.9	1.26	289.0	1.03
A25	110.00	8.00	18.00	33.00	-	-	44.00	592	222.1	274.8	1.24	286.0	1.04
A26	110.00	8.00	18.00	33.00	-	-	44.00	592	222.1	273.9	1.24	286.0	1.04
A31	110.04	8.01	17.99	25.02	-	40.00	60.00	647	242.6	282.1	1.16	297.4	1.05
A32	110.06	7.99	17.99	25.03	-	40.00	60.00	645	242.1	283.2	1.17	297.4	1.05
A33	110.00	8.00	18.00	25.00	-	50.00	60.00	675	253.5	284.7	1.12	295.2	1.05
A34	110.00	8.00	18.00	25.00	-	50.00	60.00	675	253.5	283.1	1.12	295.2	1.06
A35	110.00	8.00	18.00	25.00	-	80.00	60.00	736	276.3	291.1	1.05	302.8	1.04
A36	110.00	8.00	18.00	25.00	-	80.00	60.00	736	276.3	291.1	1.05	302.8	1.04
B11	110.07	8.02	17.98	55.04	55.00	80.00	-	739	277.1	327.6	1.21	345.3	1.05
B12	109.75	8.00	17.98	54.88	55.00	80.00	-	734	275.5	326.4	1.18	345.3	1.06
B21	110.00	8.00	18.00	30.00	70.00	80.00	50.00	592	222.1	275.4	1.24	291.0	1.06
B22	110.00	8.00	18.00	30.00	70.00	80.00	50.00	592	222.1	276.3	1.24	291.0	1.05
B23	110.07	8.01	17.98	25.04	70.00	80.00	60.00	594	222.8	281.1	1.26	296.6	1.06
B24	110.03	8.00	17.99	25.02	70.00	80.00	60.00	592	222.4	279.6	1.26	296.6	1.06
B25	110.00	8.00	18.00	33.00	70.00	80.00	44.00	592	222.1	272.6	1.22	288.9	1.06
B26	110.00	8.00	18.00	33.00	70.00	80.00	44.00	592	222.1	271.2	1.22	288.9	1.07
B31	110.00	7.99	17.98	25.00	55.00	40.00	60.00	645	242.0	281.7	1.16	290.1	1.03
B32	110.06	7.98	18.00	25.03	55.00	40.00	60.00	644	241.8	283.9	1.17	290.1	1.02
B33	110.00	8.00	18.00	25.00	55.00	50.00	60.00	675	253.5	283.6	1.11	299.9	1.06
B34	110.00	8.00	18.00	25.00	55.00	50.00	60.00	675	253.5	287.6	1.13	299.9	1.04
B35	110.00	8.00	18.00	25.00	55.00	80.00	60.00	736	276.3	292.8	1.06	306.9	1.05
B36	110.00	8.00	18.00	25.00	55.00	80.00	60.00	736	276.3	291.9	1.05	306.9	1.05

3 NUMERICAL MODEL VALIDATION

3.1 Finite element model

The finite element model and analyses are made with Abaqus FE Software 6.13. A Material Non-linear Analysis (MNA) is performed using the Newton-Raphson iteration technique. The measured engineering stress-strain diagram was transferred into a true stress-true strain diagram.

3D-elements were used to model the specimens. The boundary conditions were modelled as in the test, simulating the machine grip surfaces at both ends of the specimens as clamped by setting all degrees of freedom of these surfaces equal to zero. At one end the moving grip of the machine was simulated by a translation of the grip surface. Only half the specimen was modelled making use of symmetry cutting the specimen in length direction over the plate thickness. Therefore, one translation and two rotations on the mid plane were set equal to zero. *Fig. 3* shows these boundary conditions.

An element and mesh convergence study was performed. Linear hexahedral C3D8l elements together with a mesh fineness of 2 mm in the connection area in the middle, turned out to simulate

Fig. 3. Boundary conditions: a) Grip surfaces at both specimen ends; b) Moving grip; c) Symmetry conditions

the test results sufficiently accurate with acceptable calculation times. Typical results are shown in Fig. 4 for specimen A25 without bolts. The difference in stiffness (Fig. 4b) is caused by measuring displacements in the experiments over the grips, in stead of directly on the specimen.

Fig. 4. Specimen A25: a) Mesh with fineness 2 mm in middle part; b) Load-displacement graph

In Fig. 5, typical results for specimen B21 with bolts are shown. The bolts are modelled by 3D-elements which remain elastic. Fig. 5a shows the models of the specimen itself, the connection plate and the bolts. The third bolt is there to prevent bearing to become decisive over net cross-section failure. Hole clearance is first removed in the numerical simulation before force starts to build up.

Fig. 5. Specimen B21: a) Mesh with fineness 2 mm in middle part; b) Load-displacement graph

The finite element results in terms of ultimate normal force $N_{u,fem}$ are shown in Table 1 as well. The ratio $N_{u,fem}/N_{u,exp}$ is also given. On average, this ratio for the specimens without bolts is 1.04. For specimens with bolts this ratio is on average 1.05. The finite element model is able to predict the behavior of the specimens in terms of load-displacement behavior. The failure modes of the finite element analyses correspond to those of the tests and the ultimate loads are well predicted (over-estimation of about 5%) by the finite element model. The finite element model is considered to be validated.

3.2 Strain hardening model

In section 4 a database of numerical test results is created. This is done on the basis of nominal material properties using for S235 a yield strength $f_y = 235 \text{ N/mm}^2$ and a tensile strength $f_u = 360 \text{ N/mm}^2$. However, strain hardening needs to be included as well, so a nominal strain hardening model needs to be defined. Three models are available in three different codes: EN 1993-1-5 [5], BSK99 (Swedish code) [14] and NEN6770 (Dutch code) [15]. These models are shown in *Fig. 6a* for S235.

Fig. 6. a) Three strain hardening models for S235; b) Load-displacement graph for specimen A25

To evaluate the three available strain hardening models, they were applied using the measured engineering yield strength $f_y = 283 \text{ N/mm}^2$ and a tensile strength $f_u = 449 \text{ N/mm}^2$. Subsequently engineering stresses and strains were transformed into true stresses and strains. With the three stress-strain diagrams thus obtained and the measured stress-strain diagram, analyses were made, e.g. for specimen A25, see *Fig. 6b*. The best result, though still on the conservative side, is obtained with the strain hardening model of BSK99. However, it was chosen to continue with the strain hardening model of EN 1993-1-5 to be consistent with Eurocode 3. This is ca. 11% on the safe side. It is to be noted that if the nominal strain hardening models of *Fig. 6a* are used with yield strength $f_y = 235 \text{ N/mm}^2$ and a tensile strength $f_u = 360 \text{ N/mm}^2$, the results are conservative compared to using a measured stress-strain diagram, *Fig 7*.

Fig. 7. Load displacement graph for specimen A25 – results with nominal strain hardening models compared to results with measured stress-strain diagram

4 DATABASE OF NUMERICAL TEST RESULTS

Using the nominal strain hardening of *Fig. 6a* for S235 with nominal values for yield strength $f_y = 235 \text{ N/mm}^2$ and a tensile strength $f_u = 360 \text{ N/mm}^2$, MNA simulations were performed to create a database of 347 numerical test results. Similarly, also for S460, 40 numerical test results were added to this database. The parameters that were varied were the plate width b (120 mm and 170 mm), the plate thickness t (from 8 to 26 mm in steps of 2 mm), the end and edge distances e_1 and e_2 (from $1.2d_0$ to $4t+40$ in steps of 2 or 5 mm), the pitches p_1 and p_2 (from $2.2d_0$ to $14t$ or 200 mm in

steps of 10 mm), the number of holes (2 or 3), the bolt diameter (M16, M20 and M24) and the corresponding hole diameters d_0 (18, 22 and 26 mm). Not every bolt diameter is used in combination with each plate thickness. Bolts M16 are used for plate thicknesses from 8 to 12 mm, bolts M20 for plate thicknesses from 12 to 22 mm and bolts M24 for plate thicknesses 24 and 26 mm.

The effect of bolt hole placement for plates in S235 without bolts is illustrated in *Fig. 8* for $d_0=22$ mm, $t=12$ mm and $b=120$ mm. *Fig. 9* shows similar results for plates in S235 with bolts M20.

Fig. 8. Plates without bolts, effect of bolt hole placement, $d_0=22$ mm, $b=120$ mm, $t=12$ mm, S235:
a) Load-displacement graph; b) Failure modes

Fig. 9. Plates with bolts M20, effect of bolt placement, $d_0=22$ mm, $b=120$ mm, $t=12$ mm, S235:
a) Load-displacement graph; b) Failure modes

Fig. 10. Effect of steel grades S235 and S460 on resistance for a plate without bolt with $t=24$ mm, $b=170$ mm and $d_0=26$ mm: a) Load-displacement graph; b) Failure loads

Please note that a new numbering system is used within the database, however plates without bolts

still are denoted with A and plates with bolts with B. For all configurations net cross-section failure is decisive.

Fig. 10 shows the effect of changing the steel grade from S235 into S460 for three plate configurations without bolt, with $t=24$ mm, $b=170$ mm and $d_0=26$ mm. Despite the very different load-displacement diagrams in Fig. 10a, the ratios of the ultimate resistances for S460 and S235 are in line with the ratio of the tensile strength of the materials: $f_{u,S460}/f_{u,S235} = 540/360 = 1.5$, see Fig. 10b. Therefore, it may theoretically be possible to scale all results for S235 in the database for other steel grades in order to obtain more results in the database without performing the MNA simulations by the finite element method. However, this has not been done, since more research would be required to substantiate the indication that scaling would be allowed.

5 STATISTICAL ASSESSMENT

The database of 387 numerical test results was used to perform a statistical assessment of the design rule for net-section resistance, using the procedure of Annex D of EN 1990 as further developed in the RFCS project Safebrictile. The theoretical resistance r_t of a configuration of the database is obtained from Eq. (1) combined with Eq. (3) when setting $\gamma_{M2} = 1.0$. These values are compared to numerical resistances r_e of the database equal to $N_{u,fe}$. For the statistical assessment procedure itself, the reader is referred to [6, 7]. Looking at Eqs. (1, 3), with the pitches p_1 and p_2 taken deterministically, it can be observed that four independent variables determine the net cross-section resistance: plate width b , plate thickness t , hole diameter d_0 and tensile strength f_u . For these independent variables, which have been taken equal to their nominal values in the MNA analyses creating the database, statistical distributions are required. These distributions are characterized by their statistical properties: mean values μ , standard deviations σ and coefficients of variation V . These are given in Table 2 together with their nominal values (nom.) and the ratio mean to nominal value where appropriate. In the final column of Table 2, the source of this information is indicated.

Table 2. Statistical parameters of independent variables for net cross-section failure

Variable	μ [N/mm ²]	nom. [N/mm ²]	$\mu / \text{nom.}$ [-]	σ [N/mm ²]	V [-]	Source
b	-	-	1.000	-	0.0090	[7] Safebrictile - b - I-sections
t	-	-	0.975	-	0.0250	[7] Safebrictile - t_f - I-sections
d_0	-	-	1.000	-	0.0050	[16]
f_u - S235 - $7 < t \leq 16$	430.56	360	1.196	20.49	0.0476	[17]
f_u - S235 - $16 < t \leq 40$	435.02	360	1.208	28.80	0.0662	[17]
f_u - S460 - $16 < t \leq 40$	584.17	540	1.082	18.87	0.0323	[17]

The statistical assessment was performed using these distributions. The results for Eqs. (1, 3) are shown in Table 3, columns 3 and 4 for plates with and without bolts.

Table 3. Assessment results for plates with and without bolts for net cross-section design rules of Eqs. (1, 3)

Considered set		Eqs. (1, 3)		Eqs. (4, 3)		# tests
d_0 [mm]	steel grade	V_r	γ_{M2}^*	V_r	γ_{M2}^*	
18, 22, 26	S235	0.072	1.05	0.072	1.17	347
18, 22, 26	S235	0.075	1.05	0.075	1.17	387
26	S460					

In Table 3, the partial factor is $\gamma_{M2}^* = 1.05$ as an overall value for all considered results. However, it is interesting to also consider subsets. This is done in the acceptance diagram [7] of Fig. 11a. An acceptance diagram relates $\gamma_{M2}^*/\gamma_{M2,target}$ to the coefficient of variation V_r . The acceptance limit is shown as a solid line. The greater the coefficient of variation V_r is, the more the partial factor is allowed to deviate from its target value. Results under the solid line are acceptable. If the target value for the partial factor is chosen to be $\gamma_{M2,target} = 1.11$, then all subsets show acceptable results

(Fig. 11a) with the subset of configurations in S460 without bolts close to the limit. So overall $\gamma_{M2} = 1.05$ is acceptable, but if all subsets should show acceptable results $\gamma_{M2} = 1.11$ is required.

Fig. 11. Acceptance diagram for partial factor, all subsets: a) net cross-section design rule of Eqs. (1, 3) with $\gamma_{M2,target} = 1.11$; b) modified net cross-section design rule of Eqs. (4, 3) with $\gamma_{M2,target} = 1.23$

The current value of the partial factor being $\gamma_{M2} = 1.25$, it should be possible to optimize the design rule, by e.g. omitting the factor 0.9 from Eq. (1) as suggested in [13]. This would result in the modified design rule for net cross-section resistance of Eq. (4):

$$N_{u,Rd} = \frac{A_{net} f_u}{\gamma_{M2}} \quad (4)$$

If the statistical assessment procedure is now repeated for this modified design rule, the results of Table 3 columns 5 and 6 are obtained. So overall $\gamma_{M2} = 1.17$ is acceptable. If the target value for the partial factor is taken as $\gamma_{M2,target} = 1.23$, Fig. 11b, all subsets fulfill the acceptance criterion.

6 CONCLUSIONS

In this paper, net cross-section failure of steel plates at bolt holes was studied. Test results were reported which were used to validate a numerical model. Subsequently, this numerical model was used to create a database containing 387 numerical test results. This database was used to statistically assess the current net cross-section design rule of cl. 6.2.3 of EN 1993-1-1 [1] and a modified design rule. The conclusions are as follows:

- The finite element model for net cross-section was validated against tests since the failure modes correspond and the ultimate loads are close (the finite element model over-estimates the failure load by about 5%).
- The strain hardening model of BSK99 [14] gives better results than that of EN 1993-1-5 [5].
- The strain hardening model of EN 1993-1-5 [5] was used which gives ultimate loads that are about 11% on the conservative side.
- The current net cross-section design rule of cl. 6.2.3 of EN 1993-1-1 [1] has a recommended partial factor $\gamma_{M2} = 1.25$ while this study shows that overall $\gamma_{M2} = 1.05$ is sufficient and for individual subsets the partial factor should be $\gamma_{M2} = 1.11$.
- A modified net cross-section design rule omitting the factor 0.9 from the current design rule as suggested in [13] and represented by Eqs. (4, 3) was statistically assessed showing that an overall partial factor $\gamma_{M2} = 1.17$ is sufficient and for individual subsets the partial factor should be $\gamma_{M2} = 1.23$.

More research should substantiate these findings. For that reason and in order not to deviate too much from current practice, it is advised to change the current design rule for net cross-section of cl. 6.2.3 of EN 1993-1-1 [1] into Eqs. (4, 3) while keeping the partial factor as $\gamma_{M2} = 1.25$.

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