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REPORT FOR BLIND BOLT COMPANY

DESIGN CAPACITY OF GRADE 10.9 CARBON STEEL BLIND BOLTS M10, M20 AND M24

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EXECUTIVE SUMMARY

This report was prepared by Dr Jing Cao and Dr Stephen Hicks of the New Zealand Heavy Engineering Research Association (HERA).

This report presents design capacity values and design equations for Grade 10.9 carbon steel blind bolts in accordance with the equation format specified in NZS 3404, AS 4100 and AS/NZS 5100.6. The reliability analysis has been conducted according to EN 1990, Annex D.8 and ISO 2394. The following Blind Bolt Company products, manufactured using Grade 10.9 steel rode are considered in this report：

- Blind Bolts M10
- Blind Bolts M20
- Blind Bolts M24

The steel materials for bolt coupon tests and tests for bolt design capacities, from which results were adopted in this study, were supplied by Hangzhou Iron & Steel Group Company, China. It should be emphasized however, that if it is decided by the Blind Bolt Company to change steel material supplier in the future, the design values reported herein need to be reassessed.

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1 INTRODUCTION

HERA was commissioned by the Blind Bolt Company to verify the capacities of Grade 10.9 carbon steel Blind Bolts and provide design equations complying with the format listed in NZS 3404[1], AS 4100[2] and AS/NZS 5100.6[3]. Due to the bolt material being in higher strength than the steel ply strength, the bearing strength is normally governed by the connected steel plate, which is not related to the mechanical property of the Blind Bolts. Also as per communication with Blind Bolt Company and SCI[4], it was reckoned that the shear capacity of the slotted region is the major interest to the engineers when designing with Blind Bolts. As a consequence of this, this report only covers design capacities of Blind Blots at the slotted region.

HERA received SCI report RT1303[5], entitled ‘Design resistances of blind bolts’. The following aspects from the report were adopted in the reliability analysis for M10, M20 and M24 products:

1. Test results for blind bolts in tension and in shear with slotted region.
2. Test results for combined tension/shear capacities with slotted region.
3. Blind bolt material coupon tests (3 coupon tests for each bolt diameter).

Due to the limited number of coupon tests presented [5], HERA requested the Blind Bolt Company to provide Factory Production Control information on the bolt material variation from the bolt manufacturer. Being confirmed that the document was not available, HERA requested the client to arrange a further 5 coupon tests for each bolt diameter. This aimed to obtain sufficient statistical information regarding the true variation of the blind bolt material. On 28 March 2017, HERA received the coupon test results prepared by Rotech Laboratories, in the United Kindom. The coupon test materials were supplied by Hangzhou Iron & Steel Group Company, China. It was also confirmed from the client that the material for coupon tests reported in [5] were from the same manufacturer.

HERA also received from the client dwg files showing nominal bolt dimensions and specified tolerances.

The following design aspects were investigated:

Tension and shear capacities for:

- Blind Bolts M10
- Blind Bolts M20
- Blind Bolts M24

Combined shear and tension capacities for:

- Blind Bolts M10
- Blind Bolts M20

Note that as no test results were reported in [5], the analysis for combined tension and shear capacity for M24 was not performed in this report.

The reliability analysis were analysed in accordance to EN 1990:2002, Annex D.8[7] and ISO 2394[8].

2 TECHNICAL DELIVERY REQUIREMENTS AND TOLERANCES FOR GRADE 10.9 CARBON STEEL BLIND BOLTS M10, M20 AND M24

2.1 Dimensions and geometry tolerance for Blind Bolts M10, M20 and M24

The bolt dimensions and tolerances were derived from dwg drawings received from Blind Bolt Company, which are shown in Figure 2.1, Figure 2.2 and Figure 2.3, respectively.

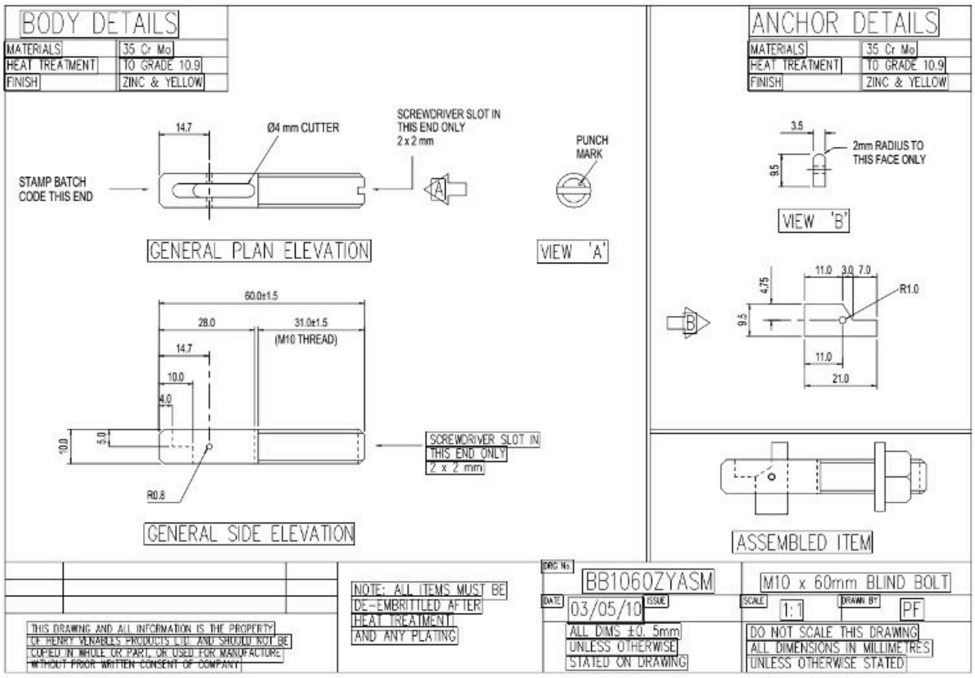

Figure 2.1 *Dimensions and geometric tolerance for blind bolts M10*

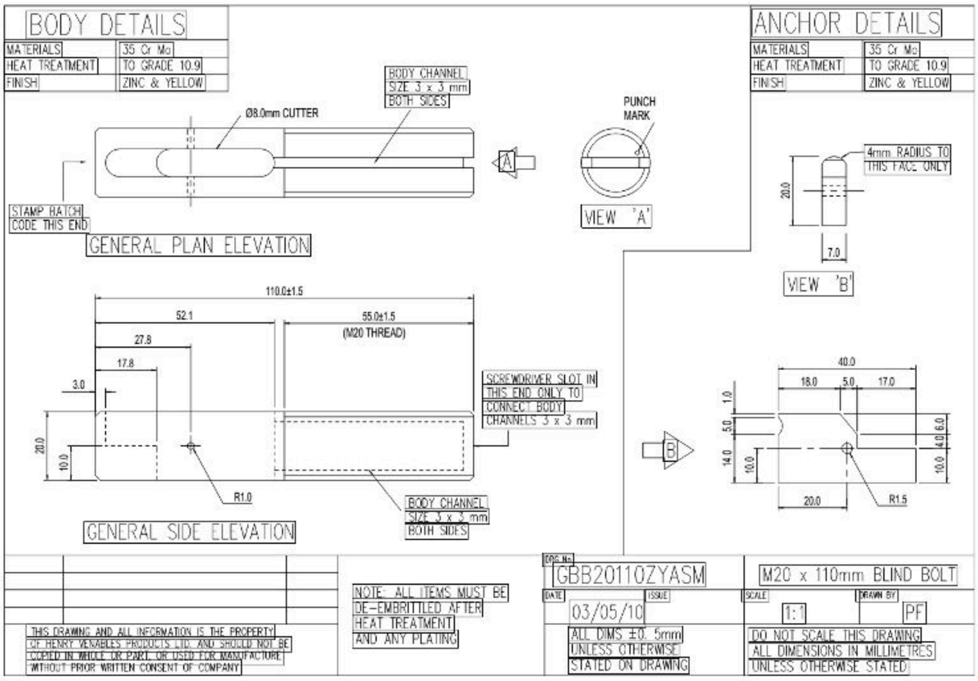

Figure 2.2 *Dimensions and geometric tolerance for blind bolts M20*

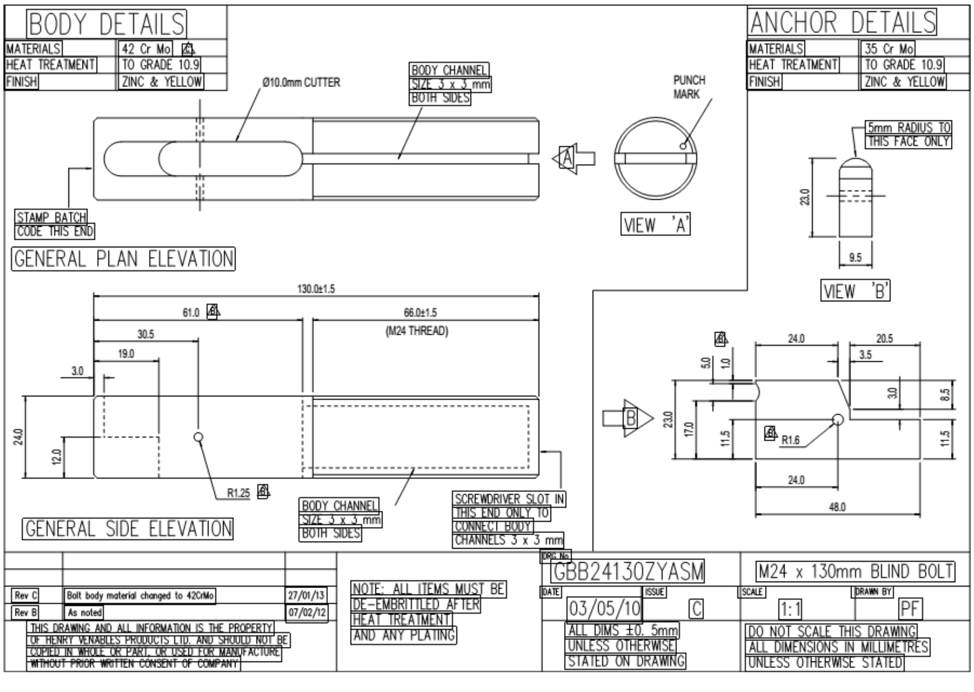

Figure 2.3 *Dimensions and geometric tolerance for blind bolts M24*

The dimensions of the blind bolts at the slotted region are presented in Figure 2.4. Derived from Figures 2.1 to 2.3, the nominal dimensions (μ) and geometrical tolerances are summarized in Table 2.1. The geometric standard deviation σ based on 2 x tolerance/$\sqrt{12}$ (assuming a rectangular distribution) and coefficient of variation (CoV=σ/μ) is also shown.

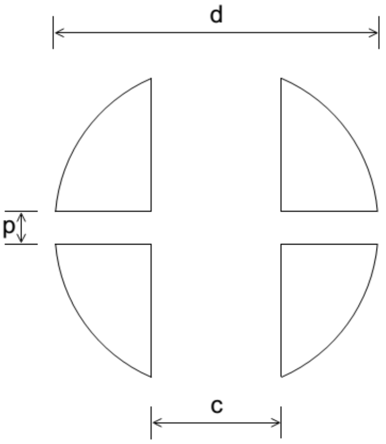

Figure 2.4 *Dimensions of blind bolts at slotted region*

Table 2.1 *Nominal Dimensions and tolerance for blind bolts at slotted region*

	Mean nominal dimensions μ mm			Tolerance mm	Standard deviation σ mm	CoV (= σ/μ) %		
	M10	M20	M24			M10	M20	M24
d	10	20	24	±0.5	0.289	2.89	1.44	1.20
c	4	8	10			7.22	3.61	2.89
p	1.6	2	2.5			18.04	14.43	11.55

2.2 Material properties for Blind Bolts M10, M20 and M24

The SCI report [4] presented 3 bolt material coupon tests for each bolt diameter. Deeming not sufficient data, HERA requested Blind Bolt Company to arrange an extra 5 coupon tests for each bolt diameter, after being confirmed that the Factory Production Control document for long-term bolt material property variation is not available. The extra coupon tests were conducted by Rotech Laboratories, the UK in accordance with the procedure specified in BS EN ISO 898-1[7].

As it is understood that the bolt material for the extra coupon tests were supplied by the same manufacturer for the tests reported in [5], the test data are analysed in one group.

Table 2.2 shows mean values, standard deviation, coefficient of variation (CoV) of the tensile strength of the bolt material f_{uf}, from the 8 coupon tests for each bolt diameter.

Table 2.2 Results from bolt material coupon tests

Data source	Test Ref.	f_{uf} MPa			Nominal strength MPa
		M10	M20	M24	
Rotech Laboratories	1	1050	1160	1130	1000*
	2	1060	1150	1090	
	3	1060	1170	1120	
	4	1070	1150	1130	
	5	1060	1150	1150	
SCI RT1303[4]	1	1113.1	1039.9	1002.5	
	2	1107.9	1056.1	1026	
	3	1101.4	1075.9	1013.8	
Mean		1078.0	1119.0	1082.8	
StD		25.3	52.4	59.6	
CoV		2.35%	4.68%	5.50%	

*Note: in the absence of values given in NZS3404, AS 4100 and AS/NZS 5100.6, the nominal ultimate tensile strength for bolts in Grade 10.9 steel are based on BS EN 1993-1-8[9].

3 DESIGN EQUATIONS AS PER NZS 3404:1997, AS 4100: 1998 AND AS/NZS 5100.6: 2017

NZS 3404:1997, AS 4100: 1998 and AS/NZS 5100.6: 2017 share a common format of design equations for bolts tension, shear and combined tension and shear capacity, which are given below.

3.1 Design of bolts in shear

NZS 3404 Cl.9.3.2.1, AS 4100 Cl.9.3.2.1 and AS/NZS 5100.6 Cl.12.5.3.1

$$V_f^* \leq \emptyset V_f \qquad \text{Equation (1)}$$

Where

V_f^* is design shear load;

$\emptyset$ is capacity reduction factor, taken as 0.8 (N.B. $\emptyset = \frac{1}{\gamma_m}$);

V_f is nominal shear capacity of a bolt;

The nominal shear capacity of a bolt (V_f) shall be calculated as follows:

$$V_f = 0.62 f_{uf} k_r (n_n A_c + n_x A_o)$$

Where

k_r is the reduction factor to account for the length of a bolted lap connection;

n_n it the number of shear planes with threads intercepting the shear plane;

A_c is the minor diameter area of the bolts;

n_x is the number of shear planes without threads intercepting the shear plane;

$\mathrm{f_{uf}}$ is minimum tensile strength of the bolt;

A_o is the nominal plain shank area of the bolt;

For blind bolts, the single shear plane capacity of slotted region is investigated. According to SCI RT 1301[4], the area of the slotted region for shear capacity Ac should be calculated as:

$$A_t = \frac{\pi d^2}{4} - \left(\frac{cd\cos\theta}{2} + \frac{d^2\theta}{2}\right) - \left(\frac{pd\cos\emptyset}{2} + \frac{d^2\emptyset}{2} - \mathrm{pc}\right) \qquad \text{Equation (2)}$$

Substituting Equation (2) into Equation (1), considering single plane shear capacity and not being relevant to the length of lap connection, (i.e. k_r=1.0), the design equation for blind bolts at slotted region for shear is:

$$V_f^* \leq \emptyset 0.62 f_{uf}\left[\frac{\pi d^2}{4}-\left(\frac{cd\cos\theta}{2}+\frac{d^2\theta}{2}\right)-(\frac{pd\cos\emptyset}{2}+\frac{d^2\emptyset}{2}-\mathrm{pc})\right] \quad \text{Equation (3)}$$

where

$\sin\theta=\frac{c}{d}$; $\sin\emptyset=\frac{p}{d}$;

Dimensions of d, p and c are shown in Figure 2.4, where p=0 for shear capacity[4].

3.2 Design of bolts in tension

NZS 3404 Cl.9.3.2.2, AS 4100 Cl.9.3.2.2 and AS/NZS 5100.6 Cl.12.5.3.2

$$N_{tf}^* \leq \emptyset N_{tf} \qquad \text{Equation (4)}$$

where

N_{tf}^* is design tension load;

$\emptyset$ is capacity reduction factor, taken as 0.8;

N_{tf} is nominal tensile capacity of bolts;

The nominal tension capacity of a bolt (N_{tf}) shall be calculated as follows:

$N_{tf}=A_s f_{uf}$

where

A_s is the tensile area of a bolt;

f_{uf} is the minimum tensile strength of the bolt.

For blind bolts, the single shear plane capacity of slotted region is investigated. According to SCI RT 1301[4], the area of slotted region for tension capacity As should be calculated as:

$$A_t=\frac{\pi d^2}{4}-\left(\frac{cd\cos\theta}{2}+\frac{d^2\theta}{2}\right)-(\frac{pd\cos\emptyset}{2}+\frac{d^2\emptyset}{2}-\mathrm{pc}) \qquad \text{Equation (5)}$$

Substituting Equation (5) into Equation (4), design equation for blind bolts at slotted region for tension is:

$$N_{tf}^* \leq \emptyset f_{uf}\left[\frac{\pi d^2}{4}-\left(\frac{cd\cos\theta}{2}+\frac{d^2\theta}{2}\right)-(\frac{pd\cos\emptyset}{2}+\frac{d^2\emptyset}{2}-\mathrm{pc})\right] \qquad \text{Equation (6)}$$

where

$\sin\theta=\frac{c}{d}$; $\sin\emptyset=\frac{p}{d}$;

Dimensions of d, p and c are shown in Figure 2.4.

3.3 Design of bolts in combined tension and shear

NZS 3404 Cl.9.3.2.3 and AS 4100 Cl.9.3.2.3 and AS/NZS 5100.6 Cl.12.5.3.3

$$\left(\frac{V_f^*}{\emptyset V_f}\right)^2 + \left(\frac{N_{tf}^*}{\emptyset N_{tf}}\right)^2 \leq 1.0 \qquad \text{Equation (7)}$$

where

$\emptyset$ is the capacity reduction factor, taken as 0.8;

V_f is the nominal shear capacity calculated from Equation (3);

N_{tf} is the nominal tensile capacity calculated from Equation (6).

The theoretical resistance for bolts shear and tension capacity adopting mean bolt dimensions and material strength in Equation (3) and Equation (6) is shown in Table 4.1 and Table 4.2. As bolt dimensions measured in the tests were not shown in [5], bolt nominal dimensions shown in Table 2.1 were used instead of mean values. The mean value for material strength was taken from Table 2.2 from coupon tests.

4 TEST RESULTS

The tests for shear, tension together with combined shear and tension have been previously reported in [5]. This section extracts test data as shown in Table 4.1 to Table 4.3, which were adopted in the reliability analysis in Section 5 and Section 6 to derive the design capacities and design equations.

Table 4.1 Shear *test results for blind bolts at slotted region [5]*

Bolt type	Test number	Maximum shear force from tests kN	Mean theoretical resistance (Equation (3)) kN	Correction factor $b_i=r_{ei}/r_{ti}$	Nominal theoretical resistance (Equation (6)) kN
M10	1	40.25	26.48	1.52	24.57
	2	33.770		1.28	
	3	32.450		1.23	
M20	1	157.49	109.99	1.43	98.29
	2	150.910		1.37	
	3	161.160		1.47	
M24	1	259.98	147.38	1.76	136.11
	2	251.80		1.71	
	3	261.07		1.77	
	4	251.57		1.71	
	5	273.38		1.86	
	6	267.13		1.81	

Table 4.2 *Tension test results for blind bolts at slotted region [5]*

Bolt type	Test number	Maximum shear force from tests kN	Mean theoretical resistance (Equation (6)) kN	Correction factor $b_i=r_{ei}/r_{ti}$	Nominal theoretical resistance (Equation (6)) kN
M10	1	18.63	32.44	0.57	30.10
	2	19.730		0.61	
	4	18.260		0.56	
	5	18.110		0.56	
M20	1	80.41	150.62	0.53	134.60
	2	81.190		0.54	
	3	84.000		0.56	
	4	81.380		0.54	
	5	85.53		0.57	
M24	1	115.20	199.92	0.58	184.64
	2	114.09		0.57	
	3	117.11		0.59	
	4	111.53		0.56	
	5	122.29		0.61	

Table 4.3 *Combined tension and shear tests for blind bolts at slotted region [5]*

Bolt type	Angle (degree)	Test number	Maximum force from tests (kN)	Tension component From tests (kN)	Shear component From tests (kN)
M10	30	1	22.88	19.81	11.44
		2	22.70	19.66	11.35
		3	22.22	19.24	11.11
	45	1	26.53	18.76	18.76
		2	29.57	20.91	20.91
		3	28.12	19.88	19.88
	60	1	38.66	19.33	33.48
		2	39.48	19.74	34.19
		3	37.86	18.93	32.79
M20	30	1	100.53	87.06	50.27
		2	97.88	84.77	48.94
		3	96.32	83.42	48.16
	45	1	125.11	88.47	88.47
		2	122.53	86.64	86.64
		3	129.31	91.44	91.44
	60	1	154.42	77.21	133.73
		2	154.53	77.27	133.83
		3	153.68	76.84	133.09

5 DESIGN VALUE AND DESIGN EQUATIONS FOR SHEAR CAPACITY OF GRADE 10.9 CARBON STEEL BLIND BOLTS M10, M20 AND M24 AS PER NZS 3404:1997, AS 4100:1998 AND AS/NZS 5100.6: 2017

5.1 Introduction

The determination of shear resistance undertaken by use of the standard evaluation procedure given in EN 1990, Annex D8.3 is presented below. V_r has been determined from previous tests using a theoretical model based on Equation (3) which is used to predict the bolt shear capacity at the slotted region. For the purposes of the evaluation, the nominal bolt dimensions in Table 2.1, measured bolt material strength in Table 2.2 were used in the models.

5.2 Selection of data for comparisons - comparison of correction factor b_i with test variables

As per Equation (3), it can be seen that the bolt diameter d (Figure 2.4) weighs highest in the shear capacity of the slotted region. Considering engineers' tradition to nominate bolt diameter in design practice, a comparison of correction factor b_i with d is plotted in Figure 5.1.

It can be seen the correction factors are reasonably constant for M10 and M20 bolts irrespective of bolt diameter d. However, M24 bolts have a higher correction factor b_i than the other two bolt diameters.

In the reliability analysis, the data points belonging to a single population are assumed to be log-normal distributed. As can be seen from Figure 5.2 which shows the log-normal distribution for all blind bolt shear tests, test data for M10 and M20 bolts form an approximate straight line, indicating that they belong to one population. M24 bolts with a steeper trend line than the other two diameters are deemed to belong to a different statistical population.

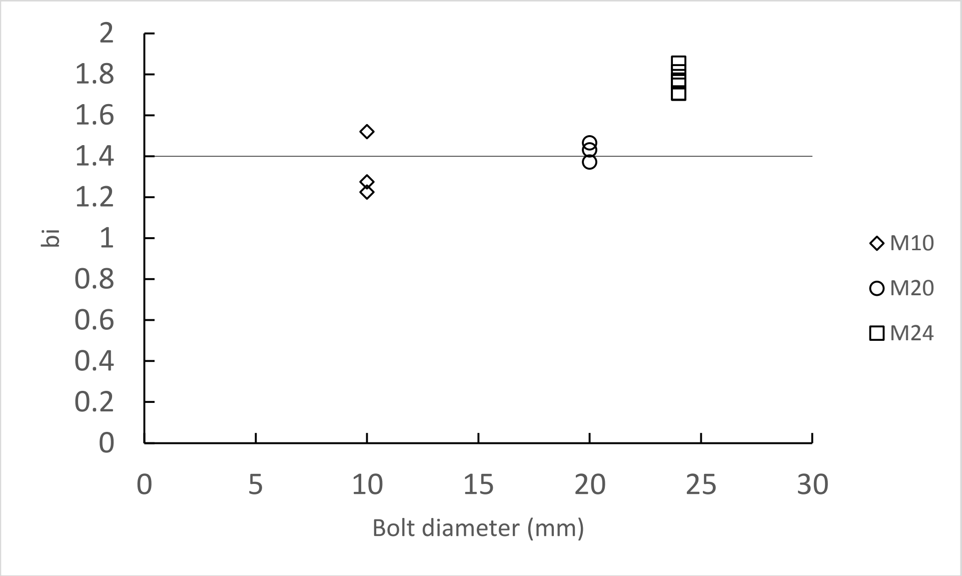

Figure 5.1 *Effect of bolt diameter d on correction factor for blind bolt shear capacity at slotted region*

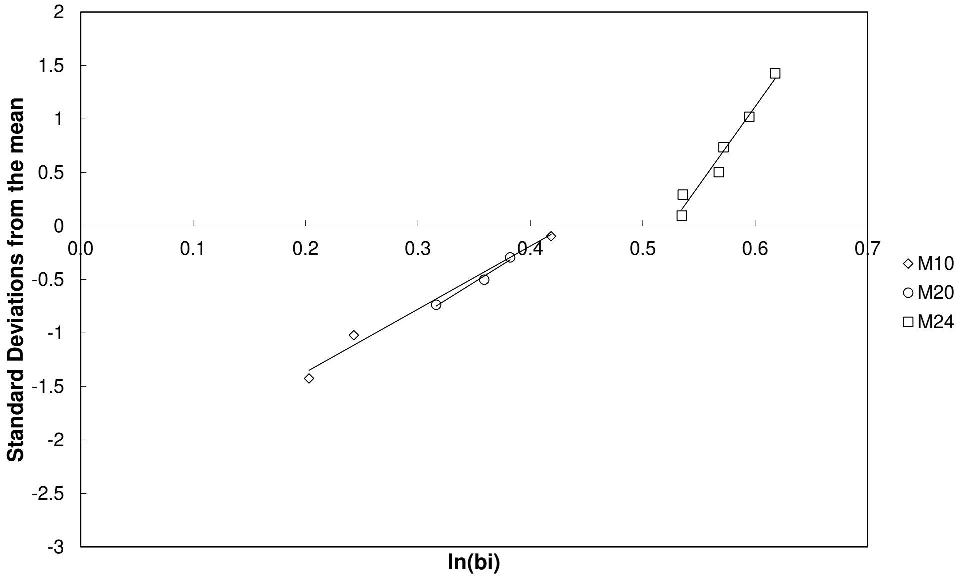

Figure 5.2 *Lognormal probability plot of correction factors for blind bolt shear capacity at slotted region*

5.3 Design values for shear capacity of blind bolts at slotted region

Coefficient of variation of the resistance function

Owing to the fact that the function for calculating the shear capacity in Equation (3) is complex, the coefficient of variation from $V_{rt}^2 = \frac{1}{g_{rt}^2(\underline{X}_m)} \times \sum_{i=1}^{j}\left(\frac{\partial g_{rt}}{\partial X_i}\sigma_i\right)^2$ was evaluated using Monte Carlo simulations. This methodology evaluates the theoretical coefficient of variation of the shear resistance V_{rt} by randomly varying the basic variables within the range of material and geometric tolerances against nominal bolt dimensions and mean material strength shown in Table 2.1 and Table 2.2.

The coefficient of variation V_{rt} is computed by conducting a large number of calculations until the results converge. A graphical example of the Monte Carlo simulation for blind bolt M10 is presented in Figure 5.3. In this case, $\boldsymbol{V_{rt}}$ **= 11.0%**.

Table 5.1 summarizes coefficient of variation V_{rt} of blind bolt M10, M20 and M24 obtained from the Monte Carlo simulations.

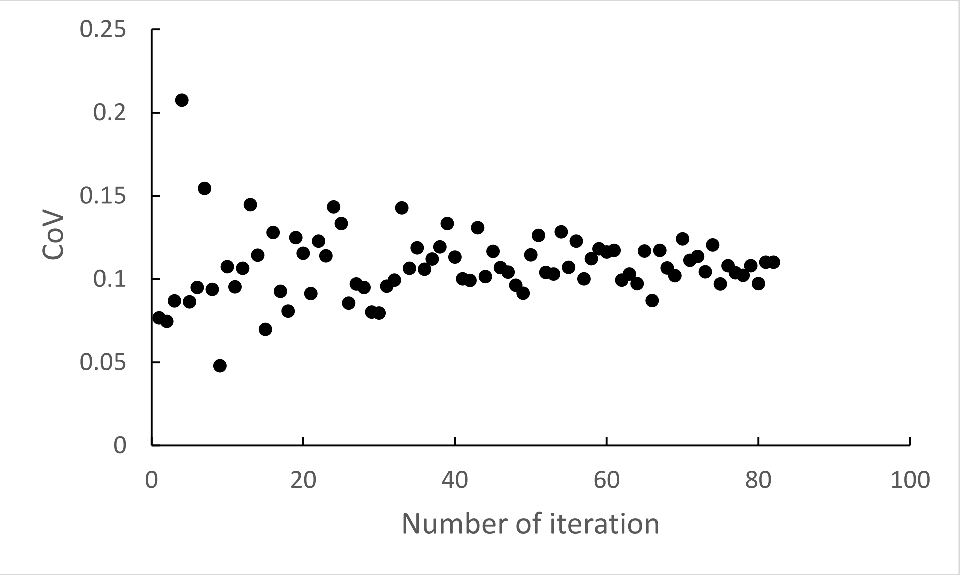

Figure 5.3 *Monte Carlo simulation for blind bolt M10 shear capacity at slotted region*

Table 5.1 Coefficient of variation V_{rt} for blind bolt shear resistance at slotted region

	M10	M20	M24
V_{rt}	11.00%	6.97%	7.39%

Design resistance evaluation according to EN 1990, Annex D.8

From Table 5.1, it can be seen V_{rt} for M10 is much larger than M20 and M24.

Although from the discussion in Section 5.2 that M10 and M20 are deemed to belong to a single population and have similar mean correction factor b_i, combining M10 and M20 in the reliability analysis to obtain design resistance may overly underestimate design value for M20. Further investigation for the design value showed that combining M10 and M20 resulted in an 18% underestimation for M20 capacity and only a 9% improvement for M10 capacity. It was decided to separate the bolt diameters in the reliability analysis.

The outcomes of the reliability analysis for shear capacity for blind bolt M10, M20 and M24 are shown in Table 5.2 to Table 5.4. Note that in these tables, $\emptyset = \frac{1}{\gamma_m^*}$.

Table 5.2 *Shear capacity for blind bolt M10 at slotted region*

EN1990 Variable	Value	EN1990 Variable	Value
n	3	V_r^2	2.533E-02
$\bar{r}_e$	35.490	Q_{rt}^2	1.204E-02
s_{re}	4.175	Q_δ^2	1.313E-02
$\bar{r}_t$	26.485	Q^2	2.501E-02
s_{rt}	0.000	α_{rt}	0.694
ρ	0.000	α_δ	0.725
b	1.340	k_n	1.90
$\overline{\Delta}$	-4.457E-03	R_k	0.745
s_Δ^2	1.313E-02	$k_{d,n}$	3.57
V_δ^2	1.322E-02	R_d	0.583
V_{rt}^2	1.211E-02	γ_M *	1.19

Table 5.3 *Shear capacity for blind bolt M20 at slotted region*

EN1990 Variable	Value	EN1990 Variable	Value
n	3	V_r^2	5.973E-03
$\bar{r}_e$	156.520	Q_{rt}^2	4.849E-03
s_{re}	5.193	Q_δ^2	1.112E-03
$\bar{r}_t$	109.987	Q^2	5.956E-03
s_{rt}	0.000	α_{rt}	0.902
ρ	0.000	α_δ	0.432
b	1.423	k_n	1.90
$\bar{\Delta}$	-3.694E-04	R_k	0.875
s_Δ^2	1.112E-03	$k_{d,n}$	3.57
V_δ^2	1.112E-03	R_d	0.782
V_{rt}^2	4.861E-03	γ_M *	0.80

Table 5.4 *Shear capacity for blind bolt M24 at slotted region*

EN1990 Variable	Value	EN1990 Variable	Value
n	6	V_r^2	6.522E-03
$\bar{r}_e$	260.822	Q_{rt}^2	5.439E-03
s_{re}	8.547	Q_δ^2	1.067E-03
$\bar{r}_t$	147.375	Q^2	6.501E-03
s_{rt}	0.000	α_{rt}	0.915
ρ	0.000	α_δ	0.405
b	1.770	k_n	1.78
$\bar{\Delta}$	-4.456E-04	R_k	0.872
s_Δ^2	1.067E-03	$k_{d,n}$	3.34
V_δ^2	1.068E-03	R_d	0.777
V_{rt}^2	5.454E-03	γ_M *	0.67

Design values for shear capacity at slotted region for blind bolt M10

From Table 5.2, the design value for blind bolt M10:

$r_d = bg_{rt}(\underline{X}_m)R_d$ =1.340 x 26.485 x 0.583=**20.678kN**

Design values for shear capacity at slotted region for blind bolt M20

From Table 5.3, the design value for blind bolt M20:

$r_d = bg_{rt}(\underline{X}_m)R_d$ =1.423 x 109.987 x 0.782=**122.459kN**

Design values for shear capacity at slotted region for blind bolt M24

From Table 5.4, the design value for blind bolt M24:

$r_d = bg_{rt}(\underline{X}_m)R_d$ =1.770 x 147.375 x 0.777=**202.617kN**

5.4 Design equations for shear capacity of blind bolts at slotted region as per NZS 3404, AS 4100 and AS/NZS 5100.6

The capacity reduction factor is defined as the ratio of design value over nominal value (see Table 3.1), i.e. $1/\gamma_M^*$ where γ_M^* is shown in Table 5.2 to Table 5.4. To avoid using different sets of reduction factor Φ in Equation (3), Φ=0.8 is kept in the new design equations but accompanied with an additional multiplier α which accounts for the difference between the design value obtained and the design resistance predicted by Equation (3), i.e.

$$\alpha = \frac{1}{\emptyset \gamma_M^*}$$

where

α is a multiplier to Equation (3) which is summarized in Table 5.5.

Φ =0.8 is the strength reduction factor as per NZS 3404, AS 4100 and AS/NZS 5100.6.

γ_M^* is derived from Table 5.2 to Table 5.3.

Table 5.5 Multiplier *α*

	M10	M20	M24
α	1.05	1.563	1.876

Design equations for shear capacity at slotted region for blind bolt M10, M20 and M24

The proposed design equation for blind bolt M10, M20 and M24 is:

$$V_f^* \leq \alpha \emptyset V_f \qquad \text{Equation (8)}$$

Where

α is adopted from Table 5.5 for blind bolt M10, M20 and M24.

$\emptyset$ is taken as 0.8.

$$V_f = 0.62 f_{uf}\left[\frac{\pi d^2}{4} - \left(\frac{cd\cos\theta}{2} + \frac{d^2\theta}{2}\right) - (\frac{pd\cos\emptyset}{2} + \frac{d^2\emptyset}{2} - \mathrm{pc})\right]$$ Equation (9)

where

$\sin\theta = \frac{c}{d}; \sin\emptyset = \frac{p}{d}$.

$\mathrm{f_{uf}}$ is tensile strength of the bolt;

d, p and c are dimensions shown in Figure 2.4, where p=0 for shear capacity.

6 DESIGN VALUE AND DESIGN EQUATIONS FOR TENSION CAPACITY OF GRADE 10.9 CARBON STEEL BLIND BOLTS M10, M20 AND M24 AS PER NZS 3404:1997, AS 4100:1998 AND AS/NZS 5100.6: 2017

6.1 Introduction

The determination of tension resistance undertaken by use of standard evaluation procedure based on EN 1990, Annex D8.3 is presented below. V_r has been determined from previous tests using a theoretical model based on Equation (6) which is used to predict the bolt tension capacity at slotted region. For the purposes of the evaluation, the nominal bolt dimensions in Table 2.1, measured bolt material strength in Table 2.2 were used in the models.

6.2 Selection of data for comparisons - comparison of correction factor b_i with test variables

As per Equation (6), it can be seen that the bolt diameter d (Figure 2.4) weighs highest in the shear capacity of the slotted region. Considering the engineers' tradition to nominate bolt diameter in design practice, a comparison of correction factor b_i with d is plotted in Figure 6.1.

It can be seen that the correction factors are reasonably constant for M10 and M24 bolts irrespective of bolt diameter d. However M20 bolts have a lower correction factor b_i than the other two bolt diameters.

In the reliability analysis, the data points belonging to a single population are assumed to be log-normal distributed. As can be seen from Figure 5.2 which shows the log-normal distribution for all blind bolt shear tests, test data for all three bolt diameters form an approximate straight line, indicating they belong to one population.

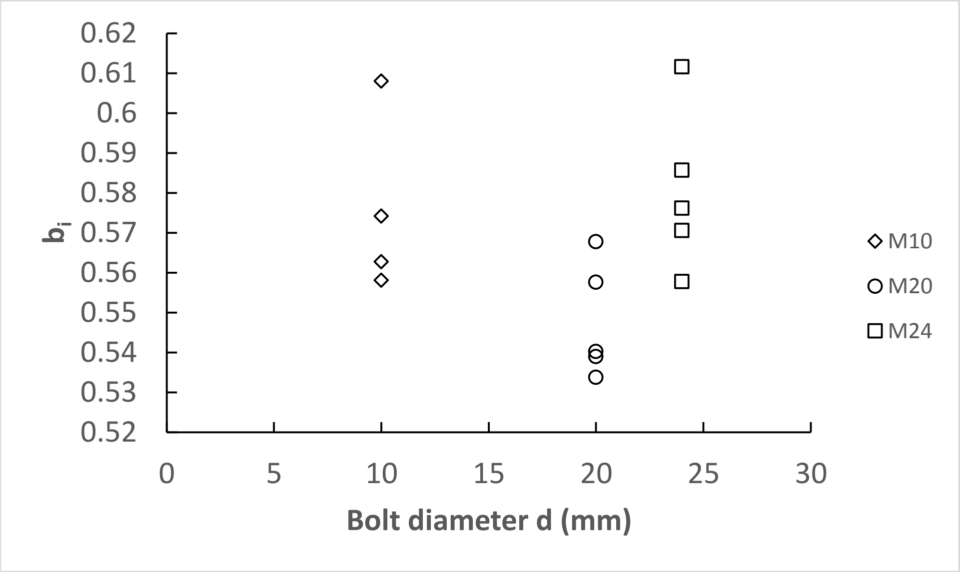

Figure 6.1 *Effect of bolt diameter d on correction factor for blind bolt tension capacity at slotted region*

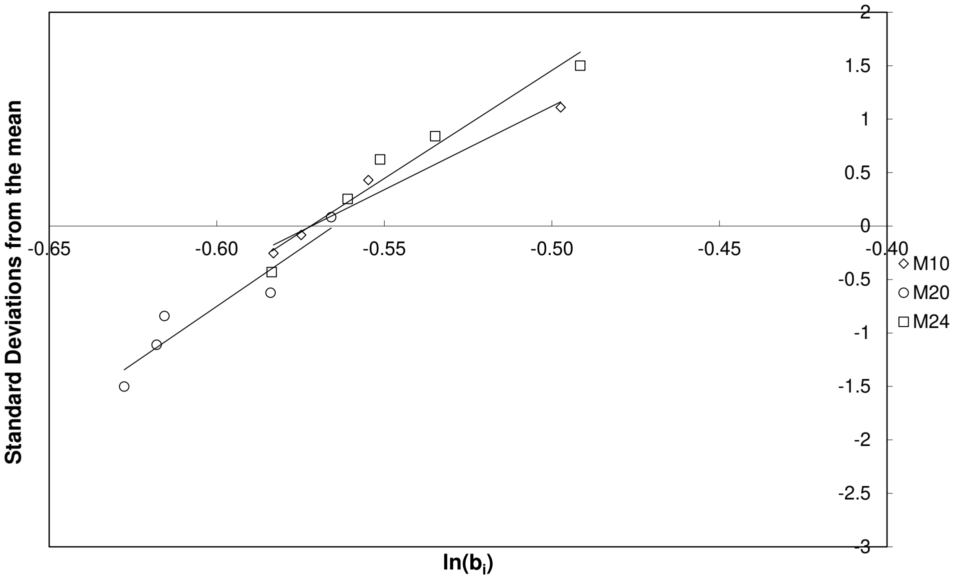

Figure 6.2 *Lognormal probability plot of correction factors for blind bolt tension capacity at slotted region*

6.3 Design values for shear capacity of blind bolts at slotted region

Coefficient of variation of the resistance function

Owing to the fact that the function for calculating the shear capacity in Equation (6) is complex, the coefficient of variation from $V_{rt}^2 = \frac{1}{g_{rt}^2(\underline{X}_m)} \times \sum_{i=1}^{j} \left(\frac{\partial g_{rt}}{\partial X_i} \sigma_i \right)^2$ was evaluated using Monte Carlo simulations. This methodology evaluates the theoretical coefficient of variation of the shear resistance V_{rt} by randomly varying the basic variables within the range of material and geometric tolerances against nominal bolt dimensions and mean material strength shown in Table 2.1 and Table 2.2.

The coefficient of variation V_{rt} is computed by conducting a large number of calculations until the results converge. A graphical example of the Monte Carlo simulation for blind bolt M10 is presented in Figure 6.3. In the case, $\boldsymbol{V_{rt}}$ **= 13.6%**.

Table 6.1 summarizes coefficient of variation V_{rt} of blind bolt M10, M20 and M24 obtained from Monte Carlo simulations.

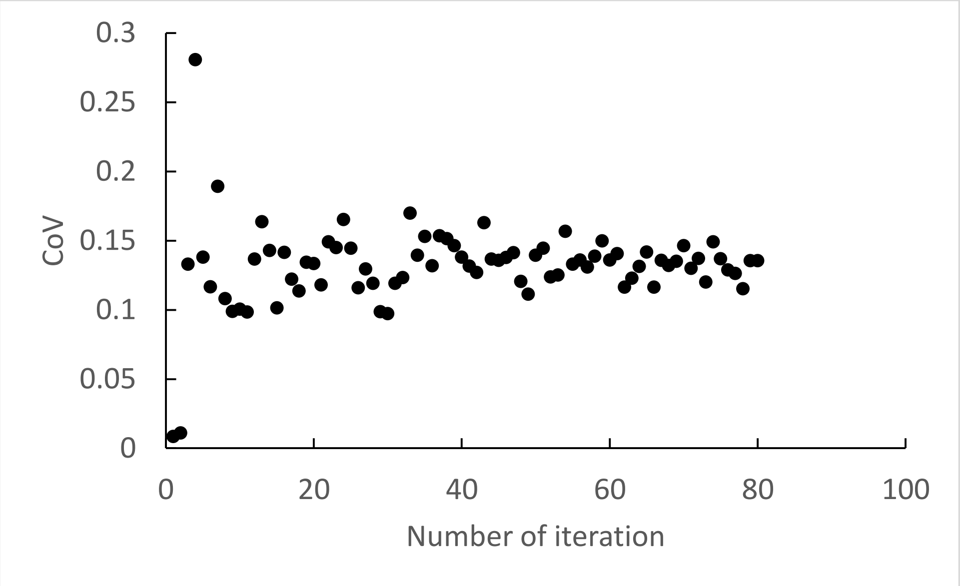

Figure 6.3 *Monte Carlo simulation for blind bolt M10 tension capacity at slotted region*

Table 6.1 Coefficient of variation V_{rt} for blind bolt tension resistance at slotted region

	M10	M20	M24
V_{rt}	13.6%	7.87%	7.44%

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Design resistance evaluation according to EN 1990, Annex D.8

From Table 6.1, it can be seen V_{rt} for M10 is much larger than M20 and M24.

Although from the discussion in Section 6.2 that M10 and M24 have similar mean correction factor b_i, and all bolt diameters are deemed to be in single population, combining M10 and M24 in the reliability analysis to obtain design resistance may overly underestimate design value for M24. Further investigation about design value showed that combing M10 and M24 resulted in 16% underestimation for M24 but only 0.6% improvement for M10. It was decided to separate the bolt diameters in the reliability analysis.

The outcomes of the reliability analysis for tension capacity for blind bolt M10, M20 and M24 are shown in Table 6.2 to Table 6.4. Note that in these tables, $\emptyset = \frac{1}{\gamma_m^*}$.

Table 6.2 *Tension capacity for blind bolt M10 at slotted region*

EN1990 Variable	Value	EN1990 Variable	Value
n	4	V_r^2	1.989E-02
$\bar{r}_e$	18.683	Q_{rt}^2	1.823E-02
s_{re}	0.732	Q_δ^2	1.492E-03
$\bar{r}_t$	32.444	Q^2	1.969E-02
s_{rt}	0.000	α_{rt}	0.962
ρ	-	α_δ	0.275
b	0.576	k_n	1.84
$\bar{\Delta}$	-5.646E-04	R_k	0.785
s_Δ^2	1.492E-03	$k_{d,n}$	3.45
V_δ^2	1.493E-03	R_d	0.643
V_{rt}^2	1.840E-02	γ_M *	2.51

Table 6.3 *Tension capacity for blind bolt M20 at slotted region*

EN1990 Variable	Value	EN1990 Variable	Value
n	5	V_r^2	6.879E-03
$\bar{r}_e$	82.502	Q_{rt}^2	6.178E-03
s_{re}	2.166	Q_δ^2	6.817E-04
$\bar{r}_t$	150.617	Q^2	6.855E-03
s_{rt}	0.000	α_{rt}	0.949
ρ	-	α_δ	0.315
b	0.548	k_n	1.80
$\bar{\Delta}$	-2.737E-04	R_k	0.869
s_Δ^2	6.817E-04	$k_{d,n}$	3.39
V_δ^2	6.819E-04	R_d	0.772
V_{rt}^2	6.197E-03	γ_M *	2.11

Table 6.4 *Tension capacity for blind bolt M24 at slotted region*

EN1990 Variable	Value	EN1990 Variable	Value
n	5	V_r^2	6.730E-03
$\bar{r}_e$	116.044	Q_{rt}^2	5.527E-03
s_{re}	4.033	Q_δ^2	1.187E-03
$\bar{r}_t$	199.921	Q^2	6.707E-03
s_{rt}	-	α_{rt}	0.908
ρ	-	α_δ	0.421
b	0.580	k_n	1.80
$\bar{\Delta}$	-4.774E-04	R_k	0.869
s_Δ^2	1.187E-03	$k_{d,n}$	3.39
V_δ^2	1.187E-03	R_d	0.773
V_{rt}^2	5.542E-03	γ_M *	2.06

Design values for tension capacity at slotted region for blind bolt M10

From Table 6.2, the design value for blind bolt M10:

$r_d = bg_{rt}(\underline{X}_m)R_d$ =0.576 x 32.444 x 0.643=**12.015kN**

Design values for tension capacity at slotted region for blind bolt M20

From Table 6.3, the design value for blind bolt M20:

$r_d = bg_{rt}(\underline{X}_m)R_d$ =0.548 x 150.617 x 0.772=**63.732kN**

Design values for tension capacity at slotted region for blind bolt M24

From Table 6.4, the design value for blind bolt M24:

$r_d = bg_{rt}(\underline{X}_m)R_d$ =0.580 x 199.921 x 0.773=**89.694kN**

6.4 Design equations for tension capacity of blind bolts at slotted region as per NZS 3404 and AS 4100

The strength reduction factor is defined as the ratio of design value over characteristic value, i.e. $1/\gamma_M^*$ where γ_M^* is shown in Table 6.2~Table 6.4. To avoid using different sets of reduction factor Φ in Equation (6), Φ=0.8 is kept in the new design equations but accompanied with an additional multiplier β which accounts for the difference between the design value and the resistance predicted by Equation (6), i.e.

$$\beta = \frac{1}{\emptyset \gamma_M^*}$$

where

β is a multiplier to Equation (6) which is summarized in Table 6.5.

Φ =0.8 is the strength reduction factor as per NZS 3404 and AS 4100.

γ_M^* is derived from Table 6.2~Table 6.3.

Table 6.5 Multiplier *α*

	M10	M20	M24
β	0.498	0.592	0.607

Design equations for tension capacity at slotted region for blind bolt M10, M20 and M24

The proposed design equation for blind bolt M10, M20 and M24 is:

$$N_{tf}^{*} \leq \beta \emptyset N_{tf} \quad \text{Equation (10)}$$

where

β is adopted from Table 6.5 for blind bolt M10, M20 and M24;

∅ is taken as 0.8.

$$N_{tf} = f_{uf}\left[\frac{\pi d^2}{4} - \left(\frac{cd\cos\theta}{2} + \frac{d^2\theta}{2}\right) - \left(\frac{pd\cos\emptyset}{2} + \frac{d^2\emptyset}{2} - \mathrm{pc}\right)\right] \qquad \text{Equation (11)}$$

$\sin\theta = \frac{c}{d}$; $\sin\emptyset = \frac{p}{d}$.

$\mathrm{f_{uf}}$ is minimum tensile strength of the bolt;

d, p and c are dimensions shown in Figure 2.4.

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7 DESIGN VALUE AND DESIGN EQUATIONS FOR COMBINED TENSION AND SHEAR CAPACITY OF GRADE 10.9 CARBON STEEL M10, M20 AND M24 AS PER NZS 3404:1997, AS 4100:1998 AND AS/NZS 5100.6: 2017

As tests for combined shear and tension were conducted only for blind bolt M10 and M20[5], this study only covers design equations for blind bolt M10 and M20 only.

Figure 7.1 and Figure 7.2 show the design envelope of combined shear and tension capacity for blind bolt M10 and M20 respectively, replacing Equation (8) and Equation (10) in Equation (7) obtained in Section 5 and Section 6. In both figures, the test data shown in Table 3.3 is also plotted.

It can be seen from both figures that by adopting design equations for shear and tension, i.e. Equation (8) and Equation (10), the combined design capacity falls well inside test data showing sufficient conservativeness. Therefore it is proposed that the following existing design equation is used:

$$\left(\frac{V_f^*}{\alpha \emptyset V_f}\right)^2 + \left(\frac{N_{tf}^*}{\beta \emptyset N_{tf}}\right)^2 \leq 1.0 \qquad \text{Equation (12)}$$

where

V_f is taken from Equation (9)

N_{tf} is taken from Equation (11)

α and β is taken from Table 5.5 and Table 6.5.

Φ is the strength reduction factor specified in NZS 3404 and AS 4100, taken as 0.8.

It should be noted that to reach the required margin of safety specified in [8], further investigation may be necessary to obtain optimized strength reduction factors other than those suggested above. The investigation is outside the work scope of this project.

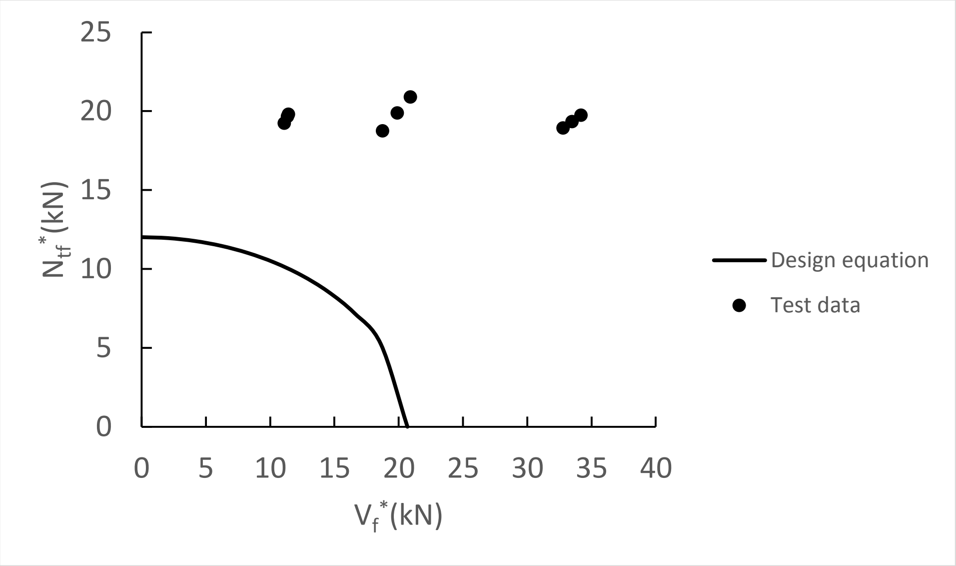

Figure 7.1 *Design envelope for the combined shear and tension capacity for blind bolt M10*

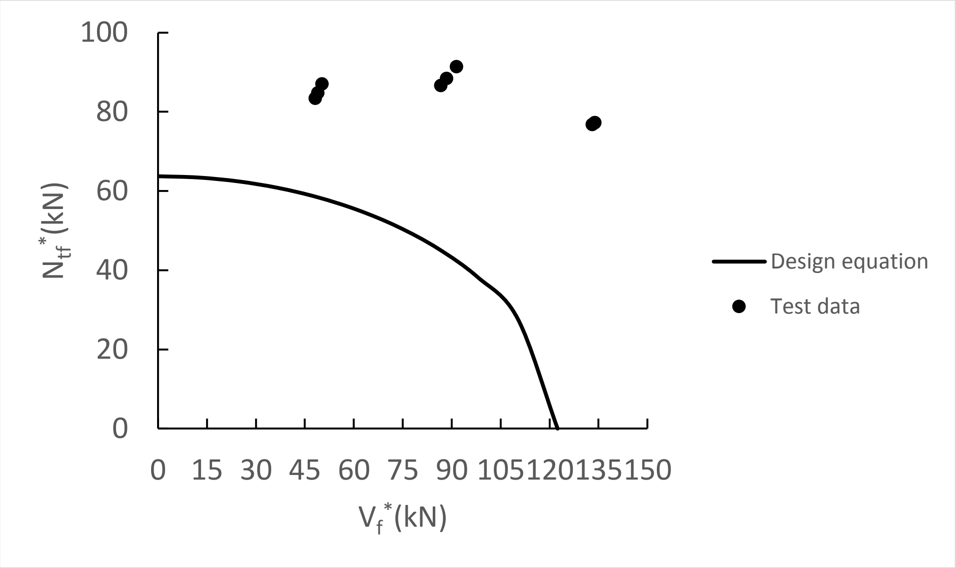

Figure 7.2 *Design envelope for the combined shear and tension capacity for blind bolt M20*

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8 CONCLUSIONS

The design values for shear capacity of blind bolt M10, M20 and M24 at slotted region is summarized in Table 8.1.

Table 8.1 *Design values for shear capacity of blind bolt M10, M20 and M24 at slotted region*

	M10	M20	M24
Design value (kN)	20.678	122.459	202.617

The design values for tension capacity of blind bolt M10, M20 and M24 at slotted region is summarized in Table 8.2.

Table 8.2 *Design values for tension capacity of blind bolt M10, M20 and M24 at slotted region*

	M10	M20	M24
Design value (kN)	12.015	63.732	89.694

The design equation for shear capacity for blind bolts M10, M20 and M24 is:

$$V_f^* \leq \alpha \emptyset V_f$$

where

V_f is taken from Equation (9).

The design equation for tension capacity for blind bolts M10, M20 and M24 is:

$$N_{tf}^* \leq \beta \emptyset N_{tf}$$

where

N_{tf} is taken from Equation (11).

The design equation for combined shear and tension capacity for blind bolts M10, M20 is:

$$(\frac{V_f^*}{\alpha \emptyset V_f})^2 + (\frac{N_{tf}^*}{\beta \emptyset N_{tf}})^2 \leq 1.0$$

In the above design equations proposed, α, β and Φ values can be derived from table below:

	M10	M20	M24
α	1.05	1.563	1.876
β	0.498	0.592	0.607
Φ		0.8	

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