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Design Concrete Members with High Strength Steel Reinforcements

*Felicia[1)] and Susanto Teng[2)]

[1), 2)] *School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798*
[1)] *felicia@ntu.edu.sg*

ABSTRACT

High strength steel bars of grade higher than 500 MPa have been introduced in construction industry but the design codes have not sufficiently catered for this type of steel bar. The main advantages of using higher strength steel bars are reduction in steel volume, avoidance of steel congestion, as well as savings in materials and labour costs.

The adequacy of Eurocode 2, however, has not been sufficiently verified for concrete design using steel Grade higher than 500 MPa. In this paper, the use of the high strength steel bars in the flexural and shear designs of reinforced concrete (RC) according to Eurocode 2 was investigated based on the materials properties and available experimental data. It was found that the Eurocode 2 method tends to overestimate the strengths of concrete members reinforced with high strength steel reinforcements as compression or shear reinforcements. Simple design recommendation for Eurocode 2 is presented in this paper to ensure that the design procedure of the Eurocode 2 remains safe for high strength steel reinforcement. This recommendation serves as limit on the useable steel strength in the design equations with EC2. Comparison with the ACI Code was made as well as the recommendations of ACI Committee on Innovation Task Group.

1. INTRODUCTION

High strength steel bars (steel Grade higher than 500 MPa) have been introduced in construction industry for a number of years. It is expected that to achieve a certain capacity, a structural member reinforced with high strength steel bars will need fewer bars compared to when normal strength steel bars are used. Fewer steel bars may also lead to smaller member dimensions or reduce reinforcement congestion. Singapore has recently introduced Grade 600 MPa steel bars and engineers are wondering if any cost savings can be obtained, with the adoption of Eurocodes, without compromising safety.

The use of high strength steel bars has been shown to be advantageous as tension reinforcement in members subjected to bending (Mast et al. 2008). Meanwhile, for the use as compression or shear reinforcement, the effectiveness of high strength steel

[1)] Research Associate
[2)] Associate Professor

bars have to be investigated in relation to the relevant design procedures. EC2 does not specifically cater for the use of steel yield strength higher than 600 MPa. Essentially all higher strength steel bars are to be taken as Grade 600 MPa steel bars, with yield strength of 600 MPa. Even then, the use of EC2 for Grade higher than 500 MPa steel bars has not been fully checked against experimental results (fib 2010). As the Eurocodes are being adopted by more and more countries (fully adopted in Singapore), accommodating the use of high strength steel bars in EC2 is necessary. This paper attempts to look into the flexural and shear designs in Eurocode 2 (EC2) for structural members with regard to the use of high strength steel bars.

2. ANALYSIS OF HIGH STRENGTH STEEL REINFORCEMENTS

2.1 Stress-Strain Relationship

Figure **1** shows the stress strain curves of high strength steel bars (ASTM A1035M Grade 690 MPa bars). It shows different stress-strain relationship from normal strength steel bars (Grade 420 or 500 MPa bars) and even locally produced Grade 600 MPa bars (Natsteel Holdings Pte Ltd 2013) which have well-defined yield point. Although the initial modulus of elasticity is similar to the normal strength steel bars, the high strength steel bars do not have well-defined yield point. Therefore, the yield strengths of these steel bars are determined by the 0.2% offset method.

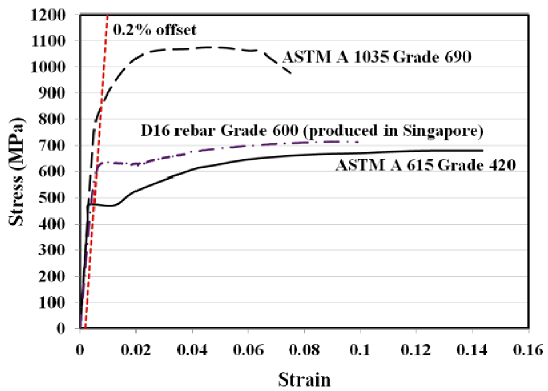


Figure 1 Stress-Strain Curves of Steel

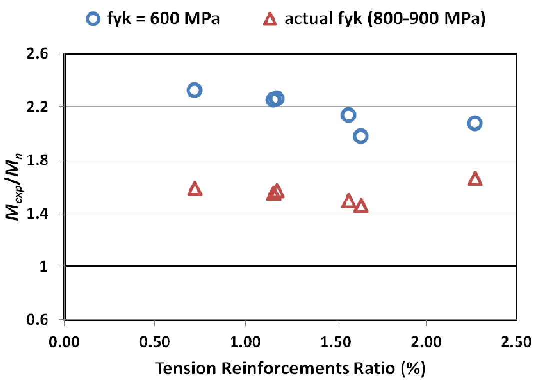


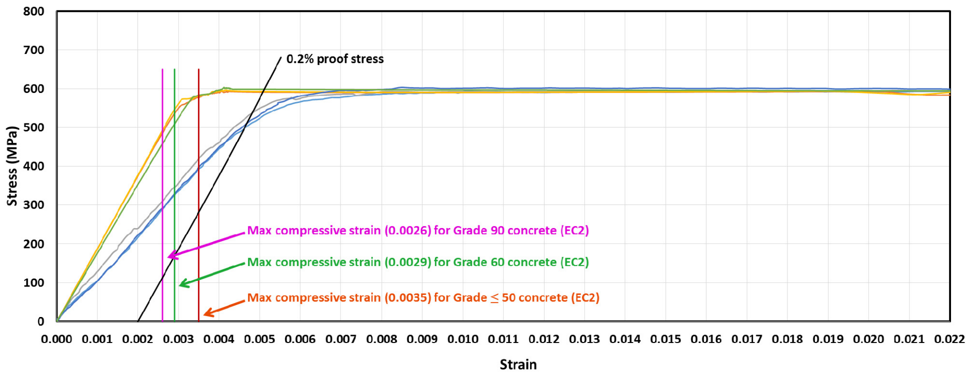
Figure 2 Comparisons of Experimental to Calculated Moment Capacity for RC Beams with High Strength Steel Bars According to EC2 with Different Limits of f_{yk}: actual f_{yk} (> 600 MPa), f_{yk} = 600 MPa

2.2 Tension Reinforcements

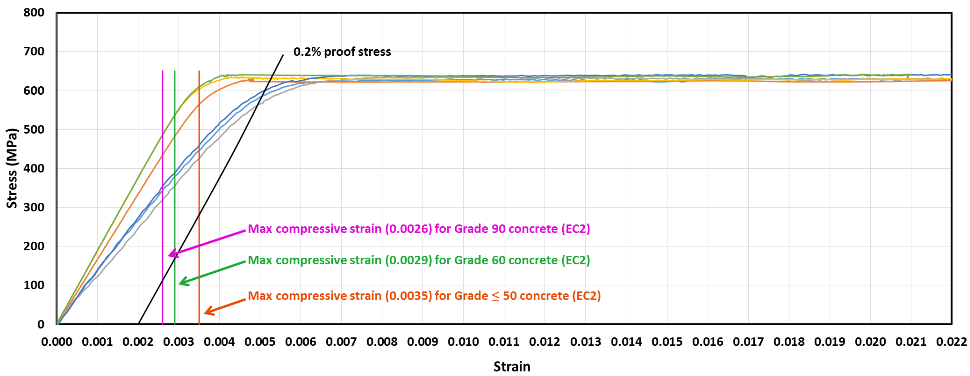
Tension reinforcements are used to resist bending in structural elements. As shown in

Figure **1**, the tensile strain corresponding to 0.2% offset is around 0.006 or higher. Therefore, ASTM A1035/A1035M specifies a minimum stress of 550 MPa corresponding to a strain of 0.0035 to ensure that the specified steel is at least as stiff at lower strains as lower-strength reinforcement bars (ACI-ITG-6 2010). For flexural design, essentially the full yield strengths of Grade 690 bars can be used as tension reinforcements according to ACI-ITG-6R-10 (ACI-ITG-6 2010). Excessive cracking and deflection should be controlled by limiting the maximum strain in the steel bars. For other applications, upper limits on the yield strengths are recommended.

Shahrooz et al. (2011) proved by their experiments that the load capacities of the beams reinforced with high strength longitudinal reinforcement (about 800-900 MPa) at the bottom of the beam are higher than the beams reinforced with normal strength longitudinal reinforcement (Grade 420 MPa). Figure 2 shows the comparison between the tested load capacities and predicted load capacities according to EC2 of the beam specimens in terms of moment capacity (M_{exp}/M_n). It can be seen that all the ratios of M_{exp}/M_n are more than 1.0, which is considered safe in terms of the strength issues without serviceability checking. However, the usable yield strength of tension reinforcement for steel Grade 600 MPa or above is limited to 600 MPa for the design according to EC2.



(a)



(b)

Figure 3 Stress-Strain Curves of: (a) Diameter 20 mm Grade 500 steel bars; (b) Diameter 16 mm Grade 600 steel bars

2.3 Compression Reinforcements

Since the concrete compression strain ε_{cu3} in EC2 is limited to 0.0035 for concrete of Grade 50 or lower, the useable steel strength for compression reinforcements should be limited to the steel stress corresponding to the concrete crushing strain of 0.0035. The steel stress corresponding to the strain of 0.0035 will depend on the composition of the steel bars or its stress-strain curve. For high strength steel bars, the stress-strain curves start to bend at about 0.8-0.85 of its 0.2% proof stress, which may lead to the stress at the strain of 0.0035 to be lower than its yield strength (0.2% proof stress). Furthermore, for concrete of Grade above 50 MPa, the ε_{cu3} is limited to a value even lower than 0.0035; i.e. 0.0029 for Grade 60 concrete and 0.0026 for concrete of Grade 90 or above. Consequently, the maximum stress in the steel bars that can be developed is also limited by those concrete compressive strains. Therefore, the usable maximum stress depends on the stress-strain curves of the steel bars and the strength of the concrete.

Figures 3(a) and 3(b) show the stress-strain curves of Grade 500 MPa steel bars (diameter 20 mm) and Grade 600 MPa steel bars (diameter 16 mm) produced by Natsteel Holdings Pte Ltd (2013). It can be seen from Figure 3(a) that Grade 500 steel bars are able to reach a stress of 500 MPa even at a strain of 0.0026 (Grade 90 concrete). Therefore, the full yield strength of Grade 500 steel bars can be used in the flexural design with EC2 as compression reinforcements. However, for Grade 600 steel bars, it can be seen from Figure 3(b) that the stresses are less than 600 MPa at the strain of 0.0035 due to the bend in the curves. It means that the full strength of Grade 600 steel bars represented by those curves is not available for compression reinforcement, even in Grade 50 concrete (ε_{cu3} of 0.0035). The steel stress will be lower at a lower concrete strain; i.e. ε_{cu3} of 0.0026 for Grade 90 concrete. Therefore, the useable strength of the steel bars in the design with EC2 for reinforcement carrying compression should be limited to 500 MPa.

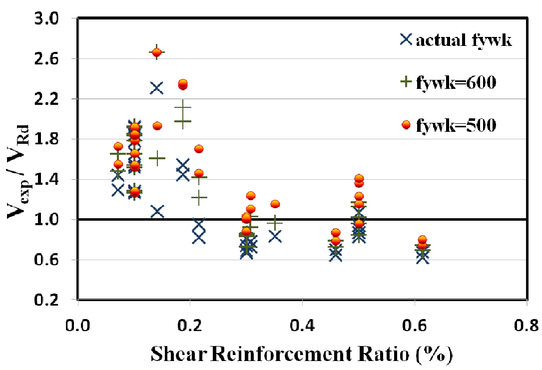


Figure 4 Comparisons of Experimental to Calculated Shear Capacity for RC Beams with High Strength Steel Bars

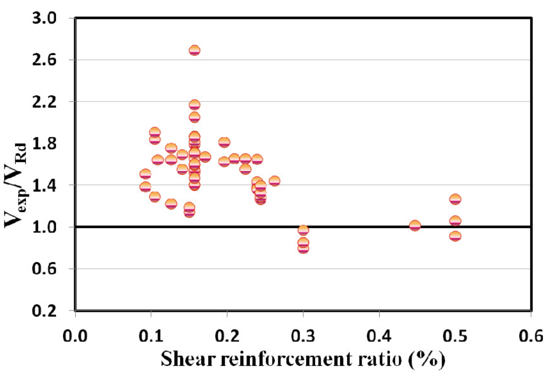


Figure 5 Comparisons of Experimental to Calculated Shear Capacity for RC Beams with 500 MPa ≤ f_{ywk} ≤ 600 MPa

According to EC2 with Different Limits of f_{ywk}: actual f_{ywk} (> 600 MPa), f_{ywk} = 600 MPa, and f_{ywk} = 500 MPa

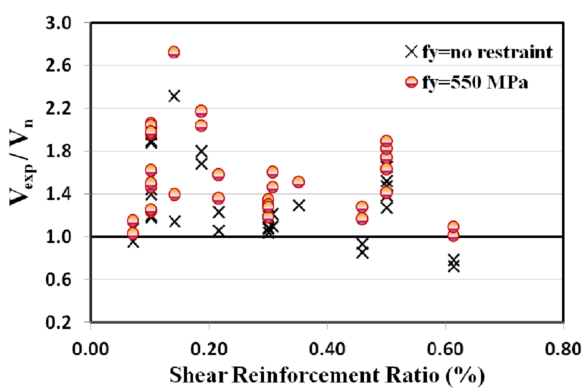
Steel Bars According to EC2

2.4 Shear Reinforcements

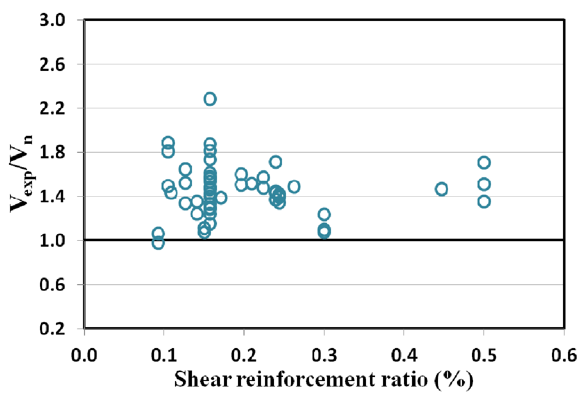
Shear design according to EC2 accommodates steel strength up to 600 MPa. However, the available safety margin in using steel bars of Grade higher than 500 MPa have not been adequately investigated (fib 2010). The use of higher strength steel bars as shear reinforcement may not lead to conservative design if the actual yield strength of the steel bars is directly substituted into the current shear equations in the EC2. Limiting the steel strength to 600 MPa for shear reinforcement may be inadequate to maintain certain level of safety margin.

Some previous studies (Sarsam and Al-Musawi 1992, Kong and Rangan 1998, Sumpter et al. 2009, Lee et al. 2011, Munikrishna et al. 2011, Shahrooz et al. 2011) on the use of high strength steel bars (ASTM Grade 690 MPa steel bars) as shear reinforcement in concrete beams have been conducted. The experimental shear capacities (V_{exp}) of 34 specimens are compared against the design shear resistances (V_{Rd}) according to EC2. Note that the EC2 also limits the variable angle of concrete strut θ to be between 22° - 45° in order to calculate the shear resistance V_{Rd} of the beams. It can be seen in Figure 4 that if the actual yield strengths of shear reinforcement from 0.2% offset (actual f_{ywk} > 600 MPa) are applied directly to the equations in EC2 to obtain the shear resistances, there are 53% of the specimens with V_{exp}/V_{Rd} less than 1.0. Even with the steel strength limit of 600 MPa, there are 35% of the specimens with V_{exp}/V_{Rd} less than 1.0.

It is also found that the design equations in EC2 for steel Grade 500 MPa is not as safe as predicted. As seen in Figure 5, 14.5% of 55 RC beams (Kong and Rangan 1998, Cladera and Marí 2005, Lee et al. 2011, Munikrishna et al. 2011) with the yield strength f_{ywk} between 500 MPa and 600 MPa have V_{exp}/V_{Rd} less than 1.0. Higher shear reinforcement ratio also may not lead to conservative design. The specimens with V_{exp}/V_{Rd} less than 1.0 have shear reinforcement ratio of 0.3% or above and yield strength f_{ywk} of 550 MPa or above.



(a)



(b)

Figure 6 Comparisons of Experimental to Calculated Shear Capacity Ratios According to ACI Code for RC Beams with High Strength Reinforcement of:
(a) f_{yt} > 600 MPa; (b) 500 MPa ≤ f_{yt} ≤ 600 Mpa

Meanwhile, the shear design V_n according to ACI Code 318-11 shows a better prediction than EC2. According to ACI-ITG-6R-10 (ACI-ITG-6 2010), a limit on yield strength f_{yt} of 550 MPa in the design equations of ACI Code 318 for ASTM A1035M Grade 690 MPa as shear reinforcement is appropriate if appearance and serviceability due to shear cracking was not a critical design consideration. Figure 6(a) shows the V_{exp}/V_n of 34 RC beams predicted with actual high strength f_{yt} and the limit of 550 MPa. It can be seen that with the f_{yt} limit of 550 MPa, there is no V_{exp}/V_n less than 1.0. Figure 6(b) also shows the V_{exp}/V_n of 55 RC beams with shear reinforcement of Grade between 500 MPa and 600 MPa; and the f_{yt} is limited to 550 MPa for actual f_{yt} above 550 MPa. The V_{exp}/V_n of all the specimens are approximately 1.0 or above.

The safety margin in the shear design equations of ACI Code 318-11 with the design yield strength limit of 550 MPa according to ACI-ITG Report has been ensured. Therefore, reducing the design yield strength of shear reinforcement f_{ywk} in the design equations of EC2 can lead to a much better safety. Limiting the f_{ywk} to 500 MPa is suggested for steel bars of Grade higher than 500 MPa.

3. RECOMMENDATION

From the discussion in the previous section, it is clear that directly uses the actual yield strength of high strength steel bars (Grade higher than 500 MPa) in EC2 design method may not be conservative, especially if it is used as compression or shear reinforcement. An easy and quick way to improve the safety margin of EC2 is limiting the yield strength of the reinforcement based on its uses in the strength designs of structural members.

In general flexural design in EC2 for structural members subjected to bending, the full yield strength of the steel bars, which is limited to 600 MPa according to EC2, can be used for tension reinforcements. For top or bottom reinforcements carrying compression in beams and slabs, the characteristic yield strength f_{yk} is limited to 500 MPa corresponding to the concrete crushing strain.

As discussed in Section 2.4, the safety of EC2 shear design method is inadequate if the full yield strength of shear reinforcement Grade higher than 500 MPa is applied directly into the equations. Therefore, the yield strength of shear reinforcement f_{ywk} is limited to 500 MPa. EC2 also specified a different design equation for punching shear resistance, which usually exists in two-way slabs and columns. The effective design strength of the punching shear reinforcement $f_{ywd,ef}$ in the equation is based on the mean of the effective depth of the members and has to be lower than the yield strength of the shear reinforcement bars f_{ywk}. Therefore, it is recommended to ensure that the $f_{ywd,ef}$ is lower than 500 MPa, or even 400 MPa is more preferable. Meanwhile, ACI-ITG-6R-10 limits the design yield strength for shear reinforcement to be 410 MPa for two-way slab design due to limited test data available that examines the punching shear strength of two-way slab systems containing Grade 690 MPa steel bars.

Table 1 shows the summary of the recommendation for EC2 and the specified yield strength recommended by ACI-ITG-6R-10 (ACI-ITG-6 2010). Note that these recommendations do not compromise the serviceability. If the appearance and serviceability due to shear cracking is concerned, the design strength of the shear reinforcement should be limited to even a lower value (ACI-ITG-6 2010). If the value of crack width or deflection is needed, then it should be calculated at a higher stress of reinforcement.

Table 1 Limit of The Yield Strengths for Structural Designs using Reinforcement Steel Grade Higher than 500 MPa

Type of Reinforcement	EC2	ACI-ITG-6R-10
Tension	600	690
Compression	500	550
Shear	500, 400 (preferable for two-way slabs)	550, 410 (for two-way slabs)

5. CONCLUSIONS

Safety margin of EC2 for designs of RC members with high strength steel bars were investigated and the conclusions are given as follow:

1. The full yield strength of Grade 600 MPa and above taken by 0.2% method can be used safely for tension reinforcements in the member designs in EC2. Since EC2 limits the yield strength to 600 MPa, the maximum yield strength of 600 MPa is suggested.
2. EC2 limit of 600 MPa for reinforcement does not have adequate safety margin when applied to compression and shear reinforcements. When the upper limit of the yield strength is taken to be 500 MPa the safety margin increases.
3. To improve EC2 safety margin, the upper limits for design yield strength f_{yk} and f_{ywk} are recommended for any actual yield strength of reinforcement. In flexural design, the upper limit of f_{yk} for tension and compression reinforcements are 600 MPa and 500 MPa respectively. In shear design, the upper limit of f_{ywk} for shear reinforcement is 500 MPa.

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