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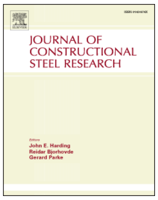

Design resistance evaluation for steel and steel-concrete composite members

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ABSTRACT

This study evaluates the performance of the design equations given in the Australian/New Zealand bridge and steel structures design standards AS 5100.6, AS 4100 and NZS 3404.1 based on reliability analysis. For this evaluation, the following two methods were utilised: (i) a capacity factor calibration method to meet the target reliability level when there are a limited number of steel yield strength tests; and (ii) an inverse reliability analysis method to calculate the required minimum number of steel yield strength tests to achieve the target reliability level when using capacity factors provided in the design standards. The methods were applied to steel and composite members including I-beams, hollow section columns, CFST columns, and composite beams. To ensure the adoptability of imported steel for these members, structural steel that conforms to European, Korean, Japanese, American, Chinese and Australasian manufacturing standards were considered in the analyses. The results showed that, for an infinite range of manufacturing data, the capacity factors were insensitive to the different manufacturing tolerances. Furthermore, when a limited number of mechanical tests were available, a much larger number of results were needed to achieve the target capacity factor for composite members in comparison with non-composite members. Finally, when considering hollow sections used as columns, the current design equations were unable to deliver the target reliability levels for any of the manufacturing standards used internationally.

List of symbols

α_R	the First Order Reliability Method (FORM) sensitivity factor for resistance
β	the reliability index
$\sigma_{\ln f_y}$	the standard deviation of the steel yield strength with the lognormal distribution
σ_r	the sample standard deviation of resistance
β_t	the target reliability index
γ_M	the partial safety factor
δ	the error of the unbiased resistance prediction
δ_i	the prediction error for each test result
ν	the degree of freedom
Φ	the cumulative distribution function of the standardised normal distribution
ϕ	the capacity factor
b	the section width of a rectangular section
d_o	the diameter of a circular section
f_{cm}	the mean measured compressive cylinder strength of concrete
f_{cu}	the mean measured compressive cube strength of concrete
f_y	the yield strength of steel
f_{yk}	the characteristic yield strength of steel
f_{ym}	the mean measured value of the yield strength
k_d	the fractile factor of the *t*-distribution corresponding to the number of test data and the target reliability index β at the 75% confidence level
$k_{d,\,Rt}$	the fractile factor corresponding to the target reliability index at the 75% confidence level, determined for a number of finite observations from a *t*-distribution
k_n	the design fractile factor for a specified probability
L_e	the effective length of a column
N	the number of experimental data
n	the size of the population
P_f	the probability of failure
R	the resistance
R_d	the design resistance
R_{ei}	the *i*-th experimental result
R_k	the lower characteristic resistance

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R_m	the sample mean value
R_n	the nominal resistance
R_{ti}	the theoretical mean resistance prediction for the *i*-th specimen
$t_\beta(\nu)$	The fractile of the *t*-distribution for the probability corresponding to the target reliability index and the number of degrees of freedom
t_p	the *p* fractile of the known *t*-distribution
u_p	the *p* fractile of the standardised normal distribution
V_R	the coefficient of variation of resistance
V_r	the sample coefficient of variation of resistance
V_{Rt}	the COV of parametric uncertainty
$V_{Rt,\ finite}$	the COV of parametric uncertainty for the parameters with a finite number of observations
$V_{Rt,\ inf}$	the COV of parametric uncertainty for the parameters with an infinite number of observations
V_δ	the COV of modelling uncertainty
$\mathbf{x}$	input parameters
$\mathbf{x}_i$	parameters used in the *i*-th specimen

1. Introduction

1.1. Background

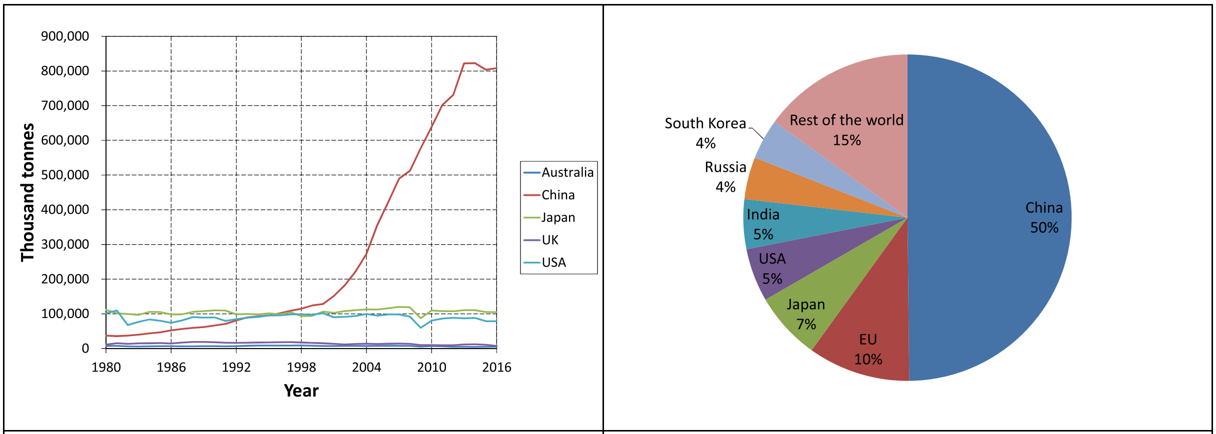
Structural steel is an international commodity that is commonly shipped thousands of miles from where it is produced to wherever there is a market. The members of the industry association worldsteel represent around 85% of world crude steel production. Fig. 1(a) presents the annual crude steel production data from worldsteel members in Australia, China, Japan, UK and USA between 1980 and 2016 [1]. As can be seen from Fig. 1(a), whilst Australia, Japan, UK and USA have broadly maintained their output, steel production in China has increased remarkably over this 36-year period. As can be seen from Fig. 1(b), China accounted for 50% of world steel production in 2016, amounting to an output of 808.4 Mt. It is therefore important for designers in the Asia-Pacific region to be able to gain access to the vast supply of Chinese made steel.

For an Asia-Pacific country who wishes to adopt the Eurocodes as their national design standard, an immediate problem is that the normative references in Eurocode 3 [2] and 4 [3] list harmonised European product and execution standards (hENs). Two options exist for designers in these countries: source steel products from mills that manufacture to hENs; or deem steel products manufactured to other standards to be equivalent in performance to hENs. Whilst the former option may be considered attractive, sourcing can be problematical and CE Marking is not mandatory in countries outside the European Economic Area where the Construction Products Regulation [4] is enforced. As a consequence of this, the latter option of accepting equivalent steel products is commonly used.

In Singapore and Hong Kong, two guides have been developed to enable designers to use alternative steel products that are deemed to have equivalent performance to hENs [5,6]. Provided that an alternative steel product is manufactured to a national standard recognized by these two guides, the steel mill is required to supply: a factory production control (FPC) certificate issued by a notified body; and a test certificate for each batch of steel product delivered to the project issued by an independent third-party inspection agency (the latter is consistent with the level of traceability required by EN 1090-2 [7] for grade S355JR and S355J0 steel in EXC2, EXC3 and EXC4 structures). Depending on the alternative steel product satisfying certain requirements [8], three product classes are defined with different partial factor values, viz. Class 1 with $\gamma_{M0} = 1.0$ (i.e. deemed to be directly equivalent to hENs, so the recommended value in Eurocode 3 and 4 is used); Class 2 with $\gamma_{M0} = 1.1$; and Class 3 with $f_{yd} = 170$ MPa for steel thicknesses not >16 mm (an identical value is given for unidentified steel in Australasia).

Whilst there are no immediate plans to adopt the Eurocodes in Australia and New Zealand, there is beginning to be greater harmonization through joint Australian/New Zealand (AS/NZS) design standards. However, in a similar way to Singapore and Hong Kong, due to a limited range of AS/NZS steel products, steel produced to British (BS and BS EN) and Japanese (JIS) standards have been used in New Zealand design for the last 35-years [9]:

Following the decision to revise the Australian steel and composite bridge design standard AS 5100.6 [10] as a joint AS/NZS standard, concerns were raised by the Committee responsible that the different cross-sectional tolerances of the structural steel products recognized in the New Zealand steel structures design standard NZS 3404.1: 1997 [11] may cause an erosion of safety margins. In response to these concerns, reliability analyses were undertaken by Kang et al. [9] for non-composite beams in bending which, unlike the Singapore [5] and Hong Kong [6] guide, directly evaluated the required capacity reduction factor ϕ (N.B. $\phi \equiv 1/\gamma_{M0}$). This work demonstrated that, for a coefficient of variation of the yield strength $V_{fy} = 10\%$ (which is consistent with the value used in the original Australian standard calibration [12]), the calculated capacity factors were insensitive to cross-sectional geometrical tolerances. More recently, the reliability analyses were extended by Uy et al. [13] to include structural steel complying with GB/T 11263 [14]; again, it was found that the capacity factors were insensitive to different tolerances. However, it was shown that there was a direct relationship between the coefficient of variation and the capacity factors where for $V_{fy} = 5\%$, 10%, 15% and 20% resulted in capacity factors of $\phi =$ 1.00, 0.94, 0.87 and 0.78, respectively, for a reliability index $\beta = 3.04$.



(a) (b)

Fig. 1. (a) annual crude steel production for Australia, China, Japan, UK and USA between 1980 and 2016 (b) percentage of world steel production by country for 2016.