Engineering Structures 365 (2026) 123156

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

# Toward a general and reliable application of overstrength in timber engineering

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A R T I C L E I N F O

*Keywords:*
Capacity design
Overstrength
Timber engineering
Structural reliability analysis
Load and resistance factor design
Failure hierarchy
Ductility

A B S T R A C T

Capacity design is fundamental to achieve ductile structural behaviour, yet its implementation in timber engineering remains challenging due to the material's inherent variability and brittleness. Existing definitions of the overstrength factor – whether based on the load-and-resistance factor design (LRFD) framework or derived from component-level structural reliability analysis – often fail to ensure the intended failure hierarchy or result in uneconomic designs. This paper revisits the concept of overstrength, focusing on the unique characteristics of timber structures, where ductility is typically provided by steel connectors with negligibly varying properties while properties of timber components exhibit significantly greater stochastic variability. A new system-based reliability concept is introduced that simultaneously accounts for interactions between actions, ductile capacities, and brittle capacities. By linking target failure probabilities for ductile and non-ductile components, the proposed definition ensures that brittle failure remains consistently less likely than ductile yielding, even in cases where the variability of the brittle, non-ductile components is much higher than of the ductile component, as common in timber engineering. A comprehensive parametric study involving 60 cases evaluates the influence of load ratios, model uncertainty, and variability in actions and capacities within structural reliability analyses. The outcome from the structural reliability-based overstrength formulation was converted into overstrength factors applicable within the LRFD framework. Results show that current overstrength provisions may be insufficient or conservative, whereas the proposed approach provides a more reliable, transparent, and adaptable basis for future code development.

## 1. Introduction

### 1.1. General recap

The structural reliability (capacity, serviceability, and durability) and reliability in use (functionality) are of major concern in the construction sector, whereby economic interests and, in particular, ecological boundaries need to be respected.

Focusing on structural reliability, unforeseen and unpredictable sudden collapses of structures need to be avoided. Structures that allow excessive plastic (non-linear) deformations, or more generally exhibit ductile behaviour due to local stress concentrations or near-limit global loading, are desirable. This is not only to provide warning of impeding structural failure or collapse, but also to potentially activate less stressed or loaded components and structural areas through local stress and global load sharing and redistribution in statically indeterminate structural systems. Such possibilities can also enhance the robustness and resilience of structures [1,2]. To ensure that plastic deformation occurs and ductility develops before brittle failure (herein understood as non-ductile, non-dissipative, and generally undesired failure modes), a clear failure hierarchy must be established that prioritises yielding and energy dissipation in ductile regions, while preventing brittle regions from becoming inelastic or reaching their capacity or ultimate deformation. According to the Load and Resistance Factor Design (LRFD) framework and the Eurocode for timber structures, EN 1995–1–1 [3], such a design requirement can be expressed by

$$R_{\mathrm{b,d}} \geq \gamma_{\mathrm{Rd}} \cdot R_{\mathrm{d,d}} \Leftrightarrow R_{\mathrm{b,k}} \cdot \frac{k_{\mathrm{mod}}}{\gamma_{\mathrm{M}}} \geq \gamma_{\mathrm{Rd}} \cdot R_{\mathrm{d,k}} \cdot \frac{k_{\mathrm{mod}}}{\gamma_{\mathrm{M}}} \tag{1}$$

with $R_{\mathrm{b,d}}$ and $R_{\mathrm{d,d}}$ as the design values of the brittle (non-ductile) and

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https://doi.org/10.1016/j.engstruct.2026.123156
Received 12 January 2026; Received in revised form 7 May 2026; Accepted 4 June 2026
Available online 20 June 2026

ductile capacities, respectively, and $R_{b,k}$ and $R_{d,k}$ as their characteristic values, usually based on 5th percentile values, $k_{mod}$ as the modification factor (which accounts for the effects of load duration and service class), $\gamma_M$ as the material safety factor and $\gamma_{Rd}$ as the so-called overstrength factor. This approach, known as capacity design (cf. [4–6]), requires that the minimum capacity of the non-ductile component acts in series with the maximum capacity of the ductile component. This establishes a clear hierarchy of structural components, ensuring that ductile failure modes occur before non-ductile ones, and that non-ductile components remain elastic and intact at least until the ductile component reaches its maximum allowed or designed deformation limit [2,7]. Although ductile and non-ductile components act in series, meaning the system is governed by the weakest capacity, there is also a need for deformation-controlled capacity design: setting limits for minimum deformations to activate ductility and energy dissipation, and for maximum deformations to meet general design requirements (e.g. interstorey drift limits), to avoid the change from ductile to brittle failure modes due to large deformations in joints [8–10], and to ensure the system remains safely below the ultimate deformations of the non-ductile components.

In general, capacity design is based on two key concepts: overstrength design, which maintains the intended failure hierarchy, and ductility, which is necessary to categorise failure modes as either brittle (non-ductile) or ductile. Regarding the latter and with a focus on timber engineering cf. [1,11,12]. While capacity design is widely accepted, particularly in earthquake engineering, ongoing discussions in timber engineering regarding overstrength and ductility highlight the need for continued transfer and further development to ensure thorough and robust implementation in design codes for timber structures.

### 1.2. Definitions for the overstrength factor with focus on timber engineering

The overstrength factor $\gamma_{Rd}$ is influenced by several parameters outlined in [13] and [14] and comprehensively discussed and specified for timber engineering in [15]. A specific feature of timber structures is that timber itself exhibits a rather (quasi-) brittle failure behaviour in most loading directions. Therefore, ductility in terms of plastic deformations and energy dissipation under cyclic loading needs to be provided by steel (metal) parts in joints, e.g. by dowel-type fasteners and fittings [16]. While the strength properties of steel display variabilities in the range of a view percentages and are usually specified as nominal (minimum) values, the strength properties of strength graded timber, regulated as characteristic values (usually based on 5th percentiles), show considerable variabilities up to 30% or even higher. Consequently, there are usually significant differences in the probabilistic representation of the ductile and non-ductile components and failure modes in timber structures, which clearly distinguishes them from steel structures. Timber structures have also limited potential for inelastic deformation capacity, which is much lower than that of steel and reinforced concrete structures. This means that elastic deformations already constitute a large proportion of the possible upper absolute deformation limits, so the potential for additional ductile deformations is rather limited [2]. Furthermore, although capacity design aims to channel ductile deformations into specific zones of structures – zones that should be accessible to facilitate inspection, maintenance, and repair [4] – in contrast to timber structures steel and reinforced concrete structures still exhibit some non-linear response outside these zones (within the structural components) and which can be accounted for in design. This circumstance might necessitate even additional design requirements for timber structures [2]. Thus, improved knowledge and capacity design rules specifically adapted for timber structures are seen as key to reducing or even eliminating such additional design requirements.

With focus on the overstrength factor $\gamma_{Rd}$, there are numerous different definitions which are summarised and discussed, for example, in [15] and [17]. Those can be classified into two groups. Focusing on earthquake design ($\gamma_M = 1.0$ and $k_{mod} = 1.0$, as maintained in the following), the first group defines overstrength factors as the ratio between the extreme upper and extreme lower percentiles of the ductile capacity within the LRFD framework, with $\gamma_{Rd} = R_{d,0.95} / R_{d,d}$ and inserted in Eq. (1) with $R_{b,d} \geq \gamma_{Rd} \cdot R_{d,d} \Leftrightarrow R_{b,d} \geq R_{d,0.95}$ ([1,7,10,13,18–20]). In contrast, overstrength factors in the second group are defined within the structural reliability framework at the component level, by treating the ductile capacity as demand (action) and the brittle capacity as resistance [17,21–26]. Here, the probability of observing brittle failure prior to ductile failure is given as $p_{f,Rd} = \mathrm{P}(R_b \leq R_d)$, i.e. a minimum safety margin between the brittle and ductile capacities is established. Based on these outcomes, $\gamma_{Rd,II}$ can be calculated as the ratio $\gamma_{Rd,II} = R_{b,d} / R_{d,d}$ and applied within the LRFD framework.

The foundation for most subsequent work on the overstrength factor within the LRFD framework was established in [1], where $\gamma_{Rd}$ is defined as the product of three partial factors (approach I), as

$$\gamma_{Rd,I} = \frac{R_{d,0.95}}{R_{d,d}} = \gamma_{sc} \cdot {}_{an} \cdot \gamma_M = \frac{R_{d,0.95}}{R_{d,0.05}} \cdot \frac{R_{d,0.05}}{R_{d,k}} \cdot \frac{R_{d,k}}{R_{d,d}} \tag{2}$$

Here, $\gamma_{sc}$ accounts for the variability within the experimentally determined ductile capacity (statistical aspect), $\gamma_{an}$ for the model bias and model uncertainty at the level of 5th percentiles (model bias and model uncertainty aspect), and $\gamma_M$ serves to prevent ductile failures with nominal reliability

According to Šušteršič et al. [18], in addition the overdesign of ductile components – that is, their higher than required capacity (design overstrength) – also needs to be considered. In other words, $\gamma_{Rd}$ should be applied to $R_{d,d}$ and not to its demand given by the action $E_d$; see also [13], [14] and [16]. This could be achieved by adding $\gamma_\eta = R_{d,d} / E_d = 1 / \eta(R_{d,d})$ as a fourth multiplication factor in Eq. (2), with $\eta(R_{d,d})$ as the degree of utilisation of the ductile capacity.

Another two multiplication factors potentially contributing to the overstrength factor in Eq. (2) can be identified from Truttalli et al. [7]. First, $\gamma_{Rd,yu} = R_{d,lim,0.95} / R_{d,y,0.05}$ to account for the two different design levels of the ductile capacity addressed by their formulation, with $R_{d,lim,0.95}$ as the design capacity at the maximum (target) deformation limit or the ultimate design capacity (95th percentiles), whichever occurs first, and $R_{d,y,0.05}$ as the 5th percentile of the ductile capacity at yielding. Secondly, $\gamma_{cyclic}(n) = f\{R_{d,cyclic,n} / R_{d,monotonic}\}$ as function of the cyclic and monotonic response of the ductile component at a set reference number of cycles ($n$), to account for differences between monotonic and cyclic responses when setting the capacity and deformation limits.

A further multiplication factor is introduced by Ottenhaus et al. [10] with $\gamma_{err} = R_{d,supplied} / R_{d,specified}$, to account for possible differences between ordered and delivered material qualities, as frequently observed in steel parts, particularly for the lower strength classes [27–30], a circumstance which is difficult to account for in practice.

The overstrength factor in the second group (structural reliability approaches, denoted in this study as approach II) is derived from structural reliability analyses at the component level, with $g(\boldsymbol{X}) = R_b - R_d = 0$ as the limit state function, where $R_d$ is the demand (action) and $R_b$ is the capacity, and with $p_{f,Rd} = \mathrm{P}(R_b \leq R_d)$ as the failure probability. This formulation provides a quantifiable safety margin between $R_d$ and $R_b$. However, as with the LRFD approaches, there is also no proof in the structural reliability group that $\mathrm{P}(R_b \leq E) = p_f(R_b) < p_f(R_d) = \mathrm{P}(R_d \leq E)$. For quantification of the safety margin, Brühl et al. [22] recommended a regulation linked with the consequence classes in EN 1990 [31]. In [14] and [26] this safety margin was set with $p_{f,Rd} = 0.04$ ($\beta_{Rd} = 1.75$) in reference to [32]. Brühl et al. [22] outlined also the need to consider a possible correlation between $R_d$ and $R_b$.

In conclusion, the overstrength factor definitions within LRFD (first group) focus solely on the ductile capacity, without any control over the safety margin for the brittle capacity. Such a control mechanism is explicitly included in the second group of overstrength factor definitions by using structural reliability approaches. However, none of the definitions in either group controls the probabilities of failure of the brittle components in interaction with the action(s) $E$ to ensure that $P(R_b \leq E) < P(R_d \leq E)$, so that these probabilities are lower for the brittle component than for the ductile component by an additional safety margin to be defined. Brandner and Azinović [15] demonstrated that current definitions for the overstrength factor from both groups can lead either to uneconomic design or to less safety than intended and even to cases where failure of the brittle component becomes more likely than that of the ductile component. This is briefly demonstrated in the following:

Fig. 1 presents two examples where the action $E$ is represented by a Gumbel distribution ($E \sim G$; coefficient of variation $CoV[E] = 30\%$), the ductile capacity $R_d$ follows a lognormal distribution ($R_d \sim LN$; $CoV[R_d] = 10\%$) with $\gamma_M = 1.0$ and $\gamma_{an} = 1.0$ and $P(R_d \leq E) = 10^{-6}$ ($\beta = 4.75$): in case (a), the brittle capacity $R_b$ also follows a lognormal distribution ($R_b \sim LN$), and the variabilities of $R_d$ and $R_b$, as relative measures, are equal with $CoV[R_d] = CoV[R_b] = 10\%$, whereas in case (b) $R_b$ follows a Weibull distribution ($R_b \sim W$; typically used for (ideally) brittle failing components) and has a higher variability of $CoV[R_b] = 25\%$. Case (a), with equal variabilities in $R_d$ and $R_b$ may be more representative of steel structures with properties varying in the upper range. In contrast, case (b), with $CoV[R_d] < CoV[R_b]$, may be relevant for reinforced concrete structures and precast concrete elements joined by metal connectors, but particularly for timber structures, where yielding, and thus ductility and energy dissipation, must be achieved at the connections by steel (metal) parts, which usually have negligible variation in strength properties.

Through these two simple cases (a) and (b) and the application of the overstrength definition according to [1], under the set boundary conditions $\gamma_{Rd} = R_{d,0.95} / R_{d,0.05} = R_{b,0.05} / R_{d,0.05}$, the necessity of controlling the safety margin between $R_d$ and $R_b$, as well as the failure probability of $R_b$ against the action $E$, is clearly demonstrated. Firstly, case (b) shows a significantly lower safety margin between $R_d$ and $R_b$ (reliability index $\beta_{case\ (a)} = 2.33$ vs. $\beta_{case\ (b)} = 1.94$), which cannot be controlled by overstrength definitions within the LRFD group. However, $\beta_{case\ (b)}$ might still fulfil the additional safety margin set by overstrength definitions from the structural reliability group as it would be the case according to the set requirements in [14] and [26] with $\beta_{Rd} \geq 1.75$ in reference to [32]. Secondly, the higher $CoV[R_b]$ and the change in the statistical distribution model for $R_b$ from lognormal to Weibull distribution result in a clearly higher probability of observing brittle failures than ductile failures, that is for the limit state function $g(Y) = R_b - E = 0$, $\beta_{case\ (a)} = 5.87 > \beta_{case\ (b)} = 3.88$ with the latter being clearly below the target safety coefficient for ductile components of 4.75. This is despite the fact that the requirement on $\gamma_{Rd}$ is met and, compared to case (a), the density function of the non-ductile component $f(R_b)$ is shifted much further to the right.

### 1.3. Objective of the study

Recognising that overstrength factors calculated according to group one and two can result in either uneconomical or even unsafe designs, Brandner and Azinović [15] proposed a new definition for the overstrength factor within the structural reliability analysis framework, as a logical consequence of system reliability analysis for in-series acting ductile and brittle failing components (referred to in this study as approach III). This approach considers the entire system of action(s) $E$ and ductile $R_d$ and brittle $R_b$ capacities acting in series. It directly translates the requirement in capacity design that $R_b$ needs to be overdesigned to ensure a ductile failure, which also means that $p_f(R_b) < p_f(R_d) \Leftrightarrow P(R_b \leq E) < P(R_d \leq E)$, with $p_f(.)$ as failure probability. Similar investigations are known for moment-resisting steel frames (cf. [33] and [34]) but not for timber structures which have to cope with greater epistemic and aleatoric uncertainties.

Focusing on statistical distribution models commonly applied and recommended for representing $\{E; R_d; R_b\}$ as well as realistic parameter settings, the aims are to substantially extend the parametric study started in [15], by considering a combination of permanent and variable actions (i.e. $G$ and $Q$), providing a more realistic mapping of typical ULS scenarios, to prepare a sound and comprehensive basis for the synthesis of possible future regulations for the overstrength factor by transferring the results from structural reliability analyses into the LRFD framework. Such recommendations are considered reasonable depending on (groups of) capacities and the ratios between the coefficients of variation of $R_b$ and $R_d$. In this context, the authors consider it relevant to address ductility and overstrength not only for accidental load scenarios but also more generally for characteristic (permanent) load scenarios. In addition, clear recommendations for the design and execution are made so that small overstrength factors remain sufficient.

## 2. Materials and methods

### 2.1. Formulation of a new concept for the overstrength factor: approach III

To achieve the target failure hierarchy with specified reliabilities across all structural levels (from structural components, fasteners and joints up to the overall structure), the interactions of both $R_d$ and $R_b$ with the action(s) $E$, as well as the interaction between $R_d$ and $R_b$, need to be considered. To address the interactions with the action, a new concept for the overstrength factor was proposed in [15], which refers to the system level but is formulated at the component level (denoted as approach III). In this approach, $R_d$ and $R_b$ are treated as independent random variables, corresponding to a clear separation of ductile and

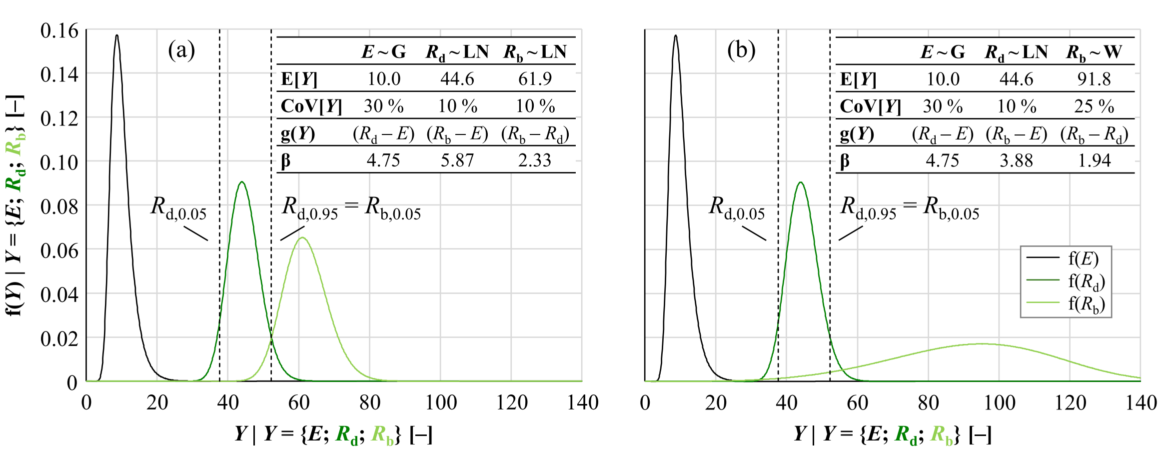


**Fig. 1.** Density functions of action ($E \sim$ Gumbel; $CoV[E] = 30\%$) and ductile ($R_d \sim$ LN; $CoV[R_d] = 10\%$) and brittle ($R_b$) capacities, aligned to satisfy $P(R_d \leq E) = 10^{-6}$ | $\beta = 4.75$ and $R_{b,0.05} = R_{d,0.95}$: (a) $R_b \sim$ LN, with $CoV[R_b] = CoV[R_d] = 10\%$; (b) $R_b \sim$ W, with $CoV[R_b] = 25\% > CoV[R_d]$; β-values from FORM analyses.

non-ductile (brittle) failure modes associated with ductile and non-ductile components. This is exemplified in timber structures, where ductility occurs in steel parts and brittle failure modes occur in timber or other components. Whereas in common design procedures the focus is on the target (nominal) failure probability $p_{f,0}$ (e.g. $p_{f,0} = 10^{-6}$ according to [31]), ensured by the limit state function $g(\boldsymbol{X_1}) = R_d - E = 0$, with failure probability $P(g(\boldsymbol{X_1}) \leq 0) = P((R_d - E) \leq 0) = p_{f,d} \leq p_{f,0}$, the specific of approach III is the explicit consideration of a second limit state function $g(\boldsymbol{X_2}) = R_b - E = 0$ with failure probability $P(g(\boldsymbol{X_2}) \leq 0) = P((R_b - E) \leq 0) = p_{f,b} \leq p_{f,d} \cdot p_{f,bd}$, where $p_{f,bd}$ is the probability of observing brittle failures prior to ductile failures under the given action (s) $E$. In the limiting case with $p_{f,d} \equiv p_{f,0}$, the additional safety for the brittle components is directly multiplied by the target probability required for the ductile capacity. With $p_{f,0} = 10^{-6}$ and $p_{f,bd} = \{10^{-1}; 10^{-2}\}$, for example, the required failure probability of brittle components becomes $p_{f,b} = \{10^{-7}; 10^{-8}\}$. As the capacities $R_d$ and $R_b$ act in series, as in [7], a small error is introduced which can be simply assessed by considering that the failure probability of serial system $p_{f,S}$ composed of $i$ independent components with failure probability $p_{f,i}$ is given as $p_{f,S} = 1 - \prod_i \left(1 - p_{f,i}\right)$, which in case of very small failure probabilities $p_{f,i}$ further simplifies to $p_{f,S} \cong \sum_i p_{f,i}$.

This new overstrength definition is also applicable in cases where brittle and ductile capacities are positively correlated, as may occur in ductile failure modes involving local plastic deformations in steel and timber. For example, this occurs in joints with laterally loaded dowel-type fasteners that fail by one or two plastic hinges per shear plane in steel fasteners, combined with embedment failure in timber. Positive correlation between $R_d$ and $R_b$ increases the safety margin ($< p_{f,Rd}$) between the two capacities $R_d$ and $R_b$ which unlike the reliability-based overstrength definitions, is not directly controlled by the simplifications made in approach III. In the extreme case of full positive correlation the failure probability of a serial system is equal to the maximum failure probability of the involved components. In the case of any negative correlation between $R_d$ and $R_b$, a rather theoretical scenario, the influence in terms of further reducing the safety margin compared to the uncorrelated case is small (cf. Melchers [35]). Anyway, to ensure that a minimum safety margin between $R_d$ and $R_b$ is maintained, additional analyses become necessary to meet not only the failure probabilities $p_{f,d} = p_{f,0}$ and $p_{f,b} = p_{f,d} \cdot p_{f,bd}$ but also $p_{f,Rd}$.

This new definition of the overstrength factor (approach III) is of utmost importance to ensure that, even in interaction with the action(s) $E$, the intended failure hierarchy – ductile before non-ductile failure modes – is achieved, including cases where $\mathrm{CoV}[R_b] > \mathrm{CoV}[R_d]$, with a safety margin to be defined and expressible via $p_{f,bd}$. In these cases, a certain but not explicitly specified value of $p_{f,Rd}$ is also automatically achieved. This second safety margin $p_{f,Rd}$ becomes relevant as an additional requirement, especially for cases with $\mathrm{CoV}[R_b] \leq \mathrm{CoV}[R_d]$, and is well addressed by the overstrength factors of approach II.

After the location parameters for the statistical distributions of $R_d$ and $R_b$ are defined in accordance with the target failure probabilities $p_{f,0}$, $p_{f,bd}$ and $p_{f,Rd}$, and after verifying both overstrength requirements (approach III: $p_{f,b} \leq p_{f,d} \cdot p_{f,bd}$, with $p_{f,b} = P(R_b \leq E)$; approach II: $p_{f,d} = P(R_d \leq E)$, and $P(R_b \leq R_d) \leq p_{f,Rd}$), the required (design relevant) overstrength factor $\gamma_{Rd}$ for use within the LRFD framework can be directly determined from $R_{b,0.05} / R_{d,0.05}$, or as the maximum of the individually calculated overstrength factors $\gamma_{Rd,III} \mid p_{f,bd}$ and $\gamma_{Rd,II} \mid p_{f,Rd}$, given as $\gamma_{Rd} = \max\{\gamma_{Rd,III}; \gamma_{Rd,II}\}$. Within this design relevant overstrength factor, $\gamma_{Rd,II}$ ensures that a specified additional safety demand between brittle and ductile failure modes is maintained, and $\gamma_{Rd,III}$ that brittle failures occur with a defined lower probability than ductile failures, a circumstance which is not fully controlled either by overstrength factors according to the LRFD framework or within the group of structural reliability analyses.

### *2.2. Representative statistical distribution models for actions and capacities and corresponding variabilities*

To create realistic settings for the intended structural reliability analyses, in which actions and capacities as random variables are probabilistically well represented, careful decisions on statistical distribution models and moments must be made, with the awareness that these choices may significantly influence the calculated probabilities of failure and, consequently, the calculated overstrength factors. Evaluation standards such as EN 14358 [36] and ISO 12491 [37] provide rules for common statistical distribution models but leave the choice to the user. In contrast, EN 1990 [31] contains more specific recommendations for statistical distribution models, and the Probabilistic Model Code (PMC) of JCSS [38] provides detailed information and recommendations for statistical distribution models for a large number of random variables, such as actions and capacities.

Table A–1 in Annex A presents recommended statistical distribution models and corresponding variabilities, expressed as coefficients of variation $\mathrm{CoV}[Y]$, for selected actions and capacities. It also includes information on steel and reinforced concrete as building materials, which are often used together or combined with timber, such as steel (metal) fasteners and fittings in joints, and timber-concrete composite (TCC) components.

### *2.3. Setting of analysed cases and applied methods*

In illustrating code calibration for structural timber, Kohler and Fink [39] treated the capacity (with $\mathrm{CoV}[Y]$ depending on the specific capacity random variable) and the model uncertainty ($\mathrm{CoV}[X] = 10\%$) as lognormally distributed random variables, permanent loads as normal ($\mathrm{CoV}[G] = 10\%$) and variable loads as Gumbel (EV-I) random variables ($\mathrm{CoV}[Q] = 40\%$). Furthermore, for timber structures typical ratios of permanent to total loads, given as $\alpha = G / (G + Q)$, were identified within the range 0.1–0.8. They addressed different design scenarios (i.e. different $\alpha_i$ values) by aligning to the target probability $p_{f,i} = P\{g_i(X; \widehat{R}; \widehat{G}; \widehat{Q})\} < 0$ and by considering the following limit state equation

$$g_i(X; \widehat{R}; \widehat{G}; \widehat{Q}) = z_i^* \cdot X \cdot \widehat{R} - \alpha_i \cdot \widehat{G} - (1 - \alpha_i) \cdot \widehat{Q} = 0 \tag{3}$$

where $z_i^*$ are calibrated design solutions with an acceptable failure probability $p_{f,i}$, $\widehat{R}$, $\widehat{G}$ and $\widehat{Q}$ are capacity, permanent and variable load, respectively, represented as random variables and normalised to a mean value of 1.00 and $X$ represents the model uncertainty. In the following, Eq. (3) is used to calculate the optimal $z_i^*$ values for designing the ductile and brittle components to the selected target probability values of $p_{f,d} = p_{f,0} = 10^{-6}$ and $p_{f,b} = \{10^{-7}; 10^{-8}\}$. The target probability $p_{f,0}$ was selecting according to EN 1990 [31] whereas the range for $p_{f,b}$ refers to publications [14] and [26] referring to regulations in [32] and [40]. Concerning the latter, it appears meaningful to limit the additional safety demand on brittle failure modes from an economical point of view. Concerning $p_{f,0}$, the PMC of the JCSS [38] relates the target safety level explicitly with the relative cost of safety measures and the consequences of failure with a range of $p_{f,0} = 10^{-3}$–$10^{-6}$ referring to a one-year reference period. To analyse a potential influence of $p_{f,0}$ on $\gamma_{Rd}$, in addition two different scenarios were analysed: $p_{f,0} = \{10^{-5}; 10^{-7}\}$. One additional variation of $p_{f,bd} = 10^{-3}$ was analysed as well.

Based on experience in statistical analysis of experimental data it is recommended to represent the strength, elastic properties, and density of timber and timber products as lognormal random variables [41]. This also applies to tension perpendicular to the grain and compression parallel to the grain, although in [38] alternative recommendations are provided. In general, it should be noted that timber, as a hierarchically organised natural material, can feature quasi-brittle to ductile failure behaviour, which is far from the ideal brittle behaviour fundamental to the Weibull theory [42].

The calculation of the optimal $z_i^*$ values in the subsequent parametric study was performed in Wolfram Mathematica v11.2 [43] using a root-finding loop function with numerical integration to estimate the failure probability. The loop function calculates the failure probability while adjusting the statistical distribution parameters to find those for which the failure probability matches the specified target. The root-finding function employs either the Newton-Raphson or a hybrid secant method. The numerical integration in [43] uses adaptive numerical quadrature for simple regions and switches to Monte Carlo (MC) sampling for complex conditions. The overstrength factors are calculated by defining the percentile ratio $\gamma_{Rd,III} = R_{b,0.05} / R_{d,0.05}$, thereby transferring the results from structural reliability analyses to the LRFD framework. The percentiles are computed analytically.

For the parametric study key sources of uncertainty and the loading ratio α were varied in the structural reliability model. Table 1 presents the key parameters analysed, which were combined to examine a total of 60 different cases. For each case, the solution was obtained in several different combinations of parameters, where the first Table B−1 considers solutions with included model uncertainties (CoV[$X$] > 0]) or without model uncertainties (CoV[$X$] = 0]) and varying $\{p_{f,bd}; p_{f,Rd}\} = \{10^{-1}; 10^{-2}\}$, while the $p_{f,0} = 10^{-6}$ remains constant. Therefore, four different solutions are presented in Table B−1 for each of the 60 cases: (i) $\gamma_{Rd,III,with\ X} \mid p_{f,b} = 10^{-7}$; (ii) $\gamma_{Rd,III,without\ X} \mid p_{f,b} = 10^{-7}$; (iii) $\gamma_{Rd,III,with\ X} \mid p_{f,b} = 10^{-8}$ and (iv) $\gamma_{Rd,III,without\ X} \mid p_{f,b} = 10^{-8}$. Additionally, Table B−2 considers one additional variation of $\{p_{f,Rd}; p_{f,bd}\} = 10^{-3}$ and two additional variations of $p_{f,0} = \{10^{-5}; 10^{-7}\}$, while model uncertainties are not considered. Altogether in Table B−2 five different solutions are presented for each case: (i) $p_{f,0} = 10^{-5} \mid \{p_{f,Rd}; p_{f,bd}\} = 10^{-1}$; (ii) $p_{f,0} = 10^{-5} \mid \{p_{f,Rd}; p_{f,bd}\} = 10^{-2}$; (iii) $p_{f,0} = 10^{-6} \mid \{p_{f,Rd}; p_{f,bd}\} = 10^{-3}$; (iv) $p_{f,0} = 10^{-7} \mid \{p_{f,Rd}; p_{f,bd}\} = 10^{-1}$; and $p_{f,0} = 10^{-7} \mid \{p_{f,Rd}; p_{f,bd}\} = 10^{-2}$.

For the reference case the underlined parameters were selected. The model uncertainty for the brittle part $X_b$ was considered as a lognormal random variable with CoV[$X_b$] = 10% and a mean value of 1.0 and was not varied in this study. This systematic variation of parameters enabled analysis of how they affect the calculated reliability for achieving ductile and brittle failure modes, and consequently the calculation of overstrength factors.

## 3. Results and discussion of the outcomes from the parametric study

### 3.1. General presentation and identification of main influencing parameters

Table B−1 in Annex B summarises the main outcomes of the parametric study, whereas the Table B−2 explores additional variations of $p_{f,0}$ and $\{p_{f,bd}; p_{f,Rd}\}$. General comments of the results therefore refer to the calculated scenarios in Table B−1, while influences shown in Table B−2 are mentioned in addition. The scaling parameter $z_b$ for the brittle capacity only applies to the determination of the overstrength factor $\gamma_{Rd,III}$ according to [15], whereas the scaling parameter for the ductile capacity $z_d$ applies to both $\gamma_{Rd,III}$ and $\gamma_{Rd,II}$. The design-relevant overstrength factor, defined as the maximum of $\{\gamma_{Rd,III}; \gamma_{Rd,II}\}$, is highlighted in bold-underlined. The overstrength factor $\gamma_{Rd,I}$ depends only on the ductile capacity; therefore, only a distinction is made with respect to its variability and thus to the consideration {with; without} model uncertainty CoV[$X$]. The overstrength factors $\gamma_{Rd,III}$ and $\gamma_{Rd,II}$ clearly depend on both, the variabilities of the ductile and brittle capacities as well as on the demanded safety margins, either between the action and the capacities or between both capacities. The analysed cases are organised in blocks: case 1 analyses the reference setting, Case 2 the influence of higher variability in permanent load CoV[$G$], cases {3; 4} the influence of the model bias E[$X$], cases {5−12} the combined influences of the share of permanent load α and the coefficient of variation of the variable load CoV[$Q$], cases {13−32} the combined influences from α and the variabilities of the ductile CoV[$R_d$] and brittle capacities CoV[$R_b$], and cases {33−60} the influences of α, CoV[$Q$], CoV[$R_d$] and CoV[$R_b$].

Based on reliability analysis the design-relevant overstrength factor is given as $\gamma_{Rd} = \max\{\gamma_{Rd,III}; \gamma_{Rd,II}\}$. The $\gamma_{Rd,III}$ ensures that the failure sequence of capacities in combination with the action – ductile prior brittle – is maintained, while $\gamma_{Rd,II}$ ensures that the extra safety margin between brittle and ductile capacities is maintained. When comparing the outcomes for the overstrength factor $\gamma_{Rd,I}$ with the design-relevant overstrength factor, there are many cases, particularly those with CoV[$R_d$] << CoV[$R_b$], for which $\gamma_{Rd,I}$ is insufficient for a safe design and for achieving the target failure hierarchy. However, there are also numerous cases where $\gamma_{Rd,I}$ imposes much higher requirements than those calculated from structural reliability analyses, resulting in uneconomic designs, especially in cases with lower safety requirements, i.e. $\{p_{f,Rd}; p_{f,bd}\} = 10^{-1}$.

Focusing on the overstrength factors $\gamma_{Rd,III}$ and $\gamma_{Rd,II}$ and considering the model uncertainties CoV[$X_d$] and CoV[$X_b$], which directly increase the variabilities of the ductile and brittle capacities, the following observations are made: the differences between $\gamma_{Rd,III}$ calculated {with; without} consideration of the model uncertainty are small. The ratio $\gamma_{Rd,III,without\ X} / \gamma_{Rd,III,with\ X}$ is on average close to 1.00 (0.99 for $p_{f,b} = 10^{-7}$ and 0.98 for $p_{f,b} = 10^{-8}$) and lies within a range of 0.94–1.04. Ratios above 1.00 are associated with α = 0.8, CoV[$R_d$] = {10; 15} % and CoV[$R_b$] = {25; 30; 35} %, i.e. a high proportion of permanent to total load combined with capacities varying in the upper range and with CoV[$R_b$] > CoV[$R_d$].

However, the influence of model uncertainty on the overstrength factor $\gamma_{Rd,II}$ is higher. The ratio $\gamma_{Rd,II,without\ X} / \gamma_{Rd,II,with\ X}$ is on average 0.92 (range 0.89–0.96) for $p_{f,b} = 10^{-7}$ and 0.88 (range 0.83–0.92) for $p_{f,b} = 10^{-8}$. The lowest values occur with low variabilities of the ductile and/or brittle capacities and vice versa for the highest values. This is because, although CoV[$X_d$] = CoV[$X_b$] = 10% are equal, the relative increase of CoV[$R_d$] and CoV[$R_b$] when including $X_d$ differs. It is higher for lower CoVs and vice versa. For example, including model uncertainty increases CoV[$R_d$] from 5% without $X_d$ to 11.2% with $X_d$, whereas CoV[$R_b$] = 25% without $X_b$ increases only to 27.0% with $X_d$.

In contrast to model uncertainty, considering the model bias E[$X_d$] > 1.00 in cases {3; 4} compared to case 1 had no apparent effect, on either $\gamma_{Rd,III}$ or on $\gamma_{Rd,II}$. This is because the increase in ductile capacity was directly compensated by higher $z_d$-values. However, in common design practice the bias coming from the engineering models used to estimate characteristic properties and/or from differences between ordered and delivered product quality may not be directly considered, may need to be estimated, or may even remain unknown. If it is possible to consider any bias from engineering models, delivered quality and/or execution at the design stage, this can be simplified by applying the multiplication factor $\gamma_{err}$ directly to the overstrength factor, i.e. $\gamma_{err} \cdot \gamma_{Rd}$, as already suggested in [10] for the quality bias.

As in real design, model bias and model uncertainty are specific to the applied engineering model. Although general consideration of model uncertainty is recommended by the PMC [38] and [39], for better

**Table 1**
Parameters and their settings as analysed by the parametric study based on the recommended statistical distribution models, CoVs and bias factors as summarised in Table A−1 in Annex A.

| parameter | **variation** (reference settings underlined) |
|---|---|
| CoV[$G$] (abbreviated "VG"); $G \sim$ N | {<u>5</u>; 10} % |
| CoV[$Q$] (abbreviated "VQ"); $Q \sim$ EV-I (Gumbel, max) | {20; <u>30</u>; 40} % |
| $\alpha = G / (G + Q)$ | {0.10; 0.50; <u>0.80</u>} |
| CoV[$R_d$] (abbreviated "VRd"); $R_d \sim$ LN | {<u>5</u>; 10; 15} % |
| E[$X_d$] \| CoV[$X_d$] = 10% (abbreviated "Xdm"); $X_d \sim$ LN | {<u>1.00</u>; 1.15; 1.30} |
| CoV[$R_b$] (abbreviated "VRb"); $R_b \sim$ LN | {10; 15; 20; <u>25</u>; 30; 35} % |

comparability and clearer discussion of the influences of varied parameters $X_d$ and $X_b$ are not considered in the following, that is the model bias is set to 1.00 and CoV[$X_d$] = CoV[$X_b$] = 0%.

In addition to Table B−1 in Annex B, the outcomes of the parametric study are visualised in Fig. 2, however, limited to the analyses without model uncertainty CoV[$X$]. As already outlined for Table B−1, the cases in Fig. 2 are grouped according to the varied parameters along the horizontal axis.

The main findings from the parametric study are summarised below, excluding those for model bias and uncertainty, which were addressed previously. The focus is on the influence of the analysed parameters on the overstrength factors $\gamma_{Rd,III}$ and $\gamma_{Rd,II}$, and on the design-relevant overstrength factor max{$\gamma_{Rd,III}$; $\gamma_{Rd,II}$}. To support these findings, the density functions of selected cases are shown in Fig. 3, with the reference case 1 in Fig. 3(a).

Case 2 analyses the possible influence of a more variable permanent load $G$, as illustrated in Fig. 3(b). Increasing CoV[$G$] from 5% to 10% does not have a significant influence on either $\gamma_{Rd,III}$ or $\gamma_{Rd,II}$. The higher CoV[$G$], in conjunction with α = 0.80, only slightly shifts the capacities $R_d$ and $R_b$ further to the right to achieve $p_{f,0} = p_{f,d} = 10^{-6}$. Although the share of $G$ in the action is 80%, the CoV[$Q$] = 30% remains much higher and its distribution is highly right-skewed, so the probabilities of failure are still dominated by the variable load.

By setting the capacities as default and varying only α and CoV[$Q$], as in cases {5−12}, $\gamma_{Rd,III}$ increases with increasing α and decreasing CoV [$Q$], i.e. in the cases analysed, it is maximal at α = 0.8 and CoV[$Q$] = 20%. The increase in $\gamma_{Rd,III}$ with increasing α is due to the greater heterogeneity and variability of the action, which results from the higher proportion of permanent load and the differences in the probabilistic characterisation of $G$ and $Q$ with respect to their probabilistic distribution models ($G$ ~ N vs. $Q$ ~ EV-I) and their variabilities, CoV[$G$] < < CoV[$Q$]; see also Fig. 3(c) compared with Fig. 3(a). Higher $\gamma_{Rd,III}$ values at lower CoV[$Q$] can be explained by the fact that, in these cases, the distance between the density functions of the ductile capacity f($R_d$) and the action f($E$) becomes smaller to satisfy the nominal failure probability $p_{f,0}$. However, as the variability in $R_b$ is much larger (CoV [$R_b$] = 25%) compared to CoV[$R_d$] = 5%, the density function of the brittle capacity f($R_b$) must lie further to the right, resulting in higher $\gamma_{Rd,III}$ values than at higher CoV[$Q$], and vice versa; see also Fig. 3(d) compared with Fig. 3(a). The overstrength factor $\gamma_{Rd,II}$ is insensitive to changes in α, CoV[$Q$], or by any combination thereof.

Cases {13−32} concentrate on the influences of CoV[$R_d$] = {5; 10; 15} %, CoV[$R_b$] = {10; 15; …; 35} % and their combinations on the overstrength factors $\gamma_{Rd,III}$ and $\gamma_{Rd,II}$, while the action, i.e. the parameters α, CoV[$G$] and CoV[$Q$], remain at their default settings. The analysis shows that combinations of high CoV[$R_b$] and low CoV[$R_d$] result in the highest $\gamma_{Rd,III}$ values; see also Fig. 3(e) and (f) compared with Fig. 3(a). This is because higher variability in the ductile capacity CoV[$R_d$] requires a greater distance between f($E$) and f($R_d$), meaning the density function of the ductile capacity needs to be further to the right to achieve $p_{f,0} = p_{f,d} = 10^{-6}$. As a result, the interaction between the action and the brittle capacity is reduced and the additional safety margin to the ductile capacity, i.e. the distance between f($R_d$) and f($R_b$), is shorter, leading to a lower $\gamma_{Rd,III}$. The demand on the overstrength factor $\gamma_{Rd,II}$ is completely opposite: it increases with decreasing CoV[$R_b$] and increasing CoV[$R_d$]. Consequently, the highest values for $\gamma_{Rd,II}$ occur for small variabilities in the brittle capacity (< CoV[$R_b$]) and large variabilities in the ductile capacity (> CoV[$R_d$]). While $\gamma_{Rd,III}$ dominates the design-relevant overstrength factor in cases where CoV[$R_d$] < < CoV[$R_b$], $\gamma_{Rd,II}$ governs cases where CoV[$R_b$] is close to CoV[$R_d$], and particularly when CoV[$R_b$] < CoV[$R_d$]; anyway, the latter two combinations are considered less relevant for timber structures.

The last block refers to cases {33−60}, which analyse various combinations of CoV[$Q$], α, CoV[$R_d$] and CoV[$R_b$]. Apart from cases {53; 54}

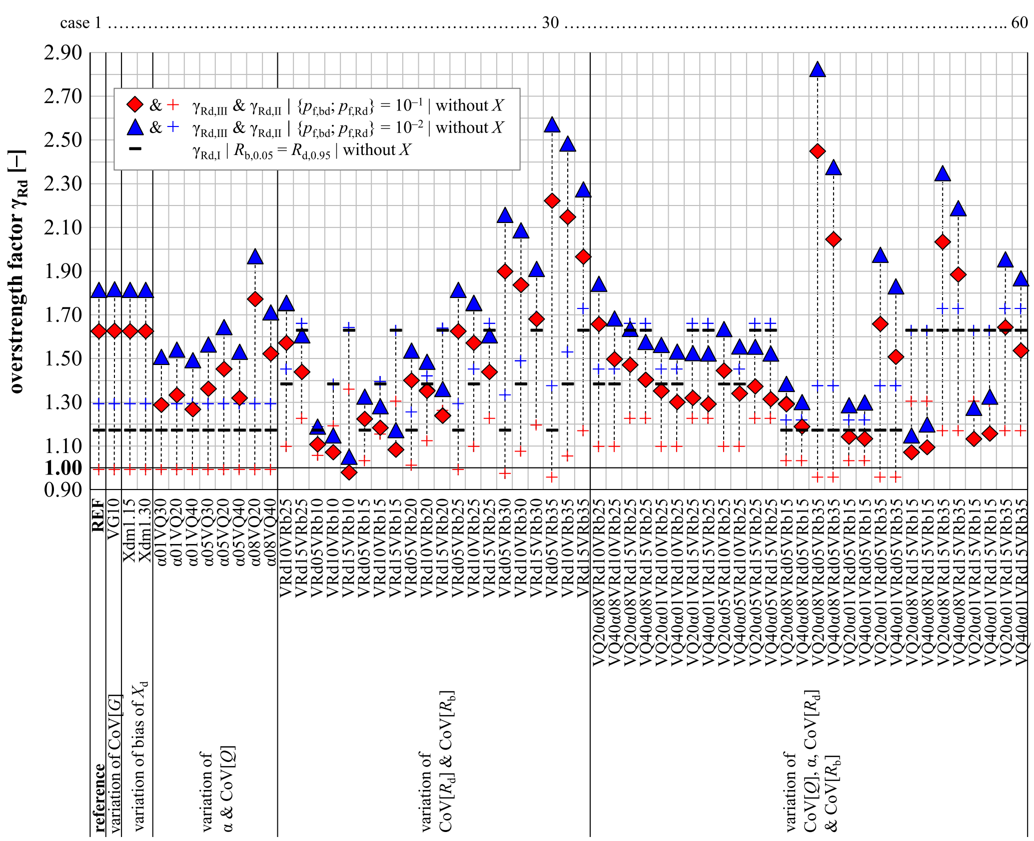


**Fig. 2.** Overstrength factors $\gamma_{Rd,III}$ for $p_{f,b} = \{10^{-7}; 10^{-8}\}$, i.e. $p_{f,bd} = \{10^{-1}; 10^{-2}\}$, based on structural reliability analyses according to [15], $\gamma_{Rd,I}$ based on LRFD according to [1] and $\gamma_{Rd,II}$ for $p_{f,Rd} = \{10^{-1}; 10^{-2}\}$ based on structural reliability analysis calculated without model uncertainty, i.e. CoV[$X$] = 0.

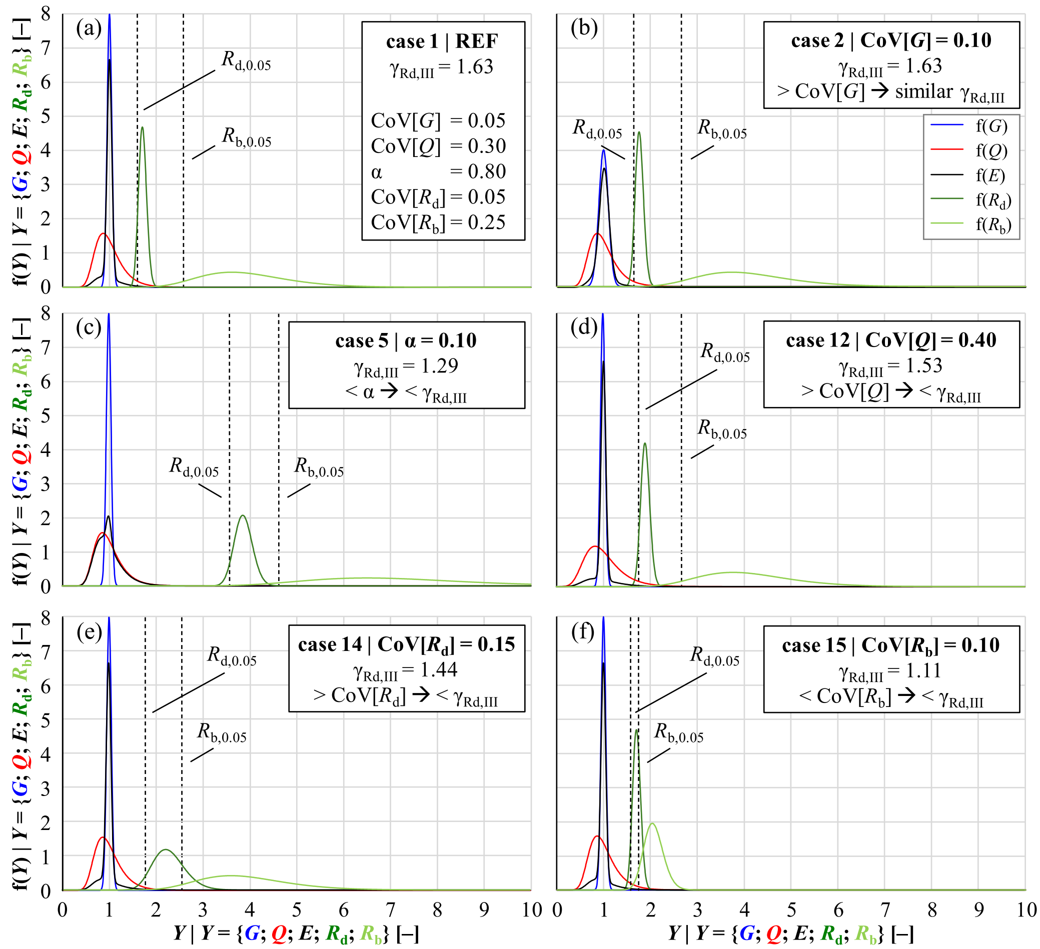


**Fig. 3.** Relationships between probability density functions for actions and capacities for selected cases from the parametric study for $p_{f,b} = 10^{-7}$ and with focus on the influence of analysed parameters apart from the model bias and uncertainty: (a) reference case (case 1); (b) increase of CoV[$G$] (Case 2); (c) increase of α (case 5); (d) increase of CoV[Q] (case 12); (e) increase of CoV[$R_d$] (case 14); (f) decrease of CoV[$R_b$] (case 15).

and {57; 58}, where CoV[$R_d$] = CoV[$R_b$] = 15%, the $\gamma_{Rd,III}$ values for CoV[$Q$] = 20% are higher than for CoV[$Q$] = 40%. The reason for this has already been mentioned: smaller variability in the variable load (< CoV[$Q$]) results in a shorter distance between f($Q$) (and more generally f($E$)) and f($R_d$) necessary to achieve the target failure probability $p_{f,0} = p_{f,d} = 10^{-6}$. Because of CoV[$R_b$] > CoV[$R_d$], the density function f($R_b$) shifts further to the right to also achieve $p_{f,b}$ = {$10^{-7}$; $10^{-8}$}. This circumstance is compensated for when CoV[$R_d$] = CoV[$R_b$]. The worst combination, i.e. the setting leading to the highest overstrength factor $\gamma_{Rd,III}$, is therefore an action dominated by permanent load (>> α) in combination with a less varying variable load (< CoV[$Q$], or overall < CoV[$E$]) and CoV[$R_d$] < < CoV[$R_b$]. The overstrength factor $\gamma_{Rd,II}$ becomes maximal with large variability in the ductile capacity (> CoV[$R_d$]) combined with small variability in the brittle capacity (< CoV[$R_b$]), whereas, by definition, it is independent of the parameters related to the action, i.e. α, CoV[$G$] and CoV[$Q$].

The increase of $p_{f,bd}$ also reflects on the increase of the overstrength factor $\gamma_{Rd,III}$. When comparing the outcomes from Table B–1 the $\gamma_{Rd,III}$ for $p_{f,b} = 10^{-8}$ are on average 1.13-times higher than for $p_{f,b} = 10^{-7}$ (range 1.07–1.21). The additional variation of $p_{f,b} = 10^{-9}$ given in Table B–2 reveals that the increase of $\gamma_{Rd,III}$ is almost linear, since the comparison between the corresponding values of $p_{f,b} = 10^{-8}$ and $p_{f,b} = 10^{-9}$ is within the range 1.07–1.21, while the average increase is 1.12. Less increase occurs for cases with α = 0.8 (e.g. heavy floors) and CoV [$R_b$] = {10; 15} % (e.g. strength properties of structural timber products such as glulam, CLT and LVL) while the higher values are found for cases with α = 0.1 (e.g. light-weight roofs) and CoV[$R_b$] = {25; 35} % (e.g. strength properties of strength graded structural timber).

For the overstrength factor $\gamma_{Rd,II}$, which depends only on the capacities, the ratio between $\gamma_{Rd,II}$ at $p_{f,Rd} = 10^{-2}$ and $\gamma_{Rd,II}$ at $p_{f,Rd} = 10^{-1}$ is on average 1.32 (range 1.12–1.47), reflecting the significant influence of the additional safety margin on $\gamma_{Rd,II}$. The additional variation for $p_{f,Rd} = 10^{-3}$ shown in Table B–2 reveals that the increase in $\gamma_{Rd,II}$ is nonproportional and is lower when $p_{f,Rd} = 10^{-3}$ is compared to $p_{f,Rd} = 10^{-2}$ (on average 1.22; range 1.09–1.33) than in the comparison between $p_{f,Rd} = 10^{-2}$ and $p_{f,Rd} = 10^{-1}$. Overall, a greater increase in overstrength factors $\gamma_{Rd,II}$ than $\gamma_{Rd,III}$ is expected with increasing {$p_{f,bd}$; $p_{f,Rd}$}. This is because the additional safety margin in $\gamma_{Rd,III}$ relates to the interaction within the tails of the density functions f($E$) and f($R_b$), whereas for $\gamma_{Rd,II}$ the densities of the brittle and ductile capacities interact to a greater extent already at much higher probabilities. The highest ratios are found for CoV[$R_b$] = {30; 35} % and the lowest ratios for CoV[$R_b$] = {10; 15} %.

Additionally, the study provides results in terms of variation of $p_{f,0}$, which can be found in Table B–2 (two additional values of $p_{f,0} = 10^{-5}$ and $p_{f,0} = 10^{-7}$ were analysed). Based on the definition of $\gamma_{Rd,II}$, the variation of $p_{f,0}$ does not influence on its calculation. On the other hand, the study shows a small influence of $p_{f,0}$ on $\gamma_{Rd,III}$. For the 60 analysed cases, a decrease of $p_{f,0}$ by a factor of $10^{-1}$ yields in a change of $\gamma_{Rd,III}$ in the range between 0.98 and 1.10, where in average $\gamma_{Rd,III}$ is increased by 1.03. The change in $\gamma_{Rd,III}$ is approximately proportional to the change in $p_{f,0}$.

### 3.2. Proposal for the regulation of the design-relevant overstrength factor

Based on the outcomes from the parametric study in Section 3.1 it is concluded that:

- overstrength factors according to the LRFD framework, such as $\gamma_{Rd,I}$, are not sufficient for a controlled design and reliable achievement of the intended failure hierarchy, ductile prior brittle, as there is no control over $p_{f,Rd}$ (interaction of $R_b$ and $R_d$) or $p_{f,bd}$ (interaction of $R_b$ and $E$);
- overstrength factors as defined within the structural reliability framework and denoted as $\gamma_{Rd,II}$ allow direct control over $p_{f,Rd}$; the calculated overstrength factors are also sufficient for the requirement $p_{f,bd}$ in cases where $\mathrm{CoV}[R_d] \geq \mathrm{CoV}[R_b]$, although there is no direct control over $p_{f,bd}$, which becomes essential in cases where $\mathrm{CoV}[R_d] < \mathrm{CoV}[R_b]$;
- the overstrength factor $\gamma_{Rd,III}$ according to [15] allows direct control over $p_{f,bd}$, which regulates the safety margin of brittle failures to ductile failures against the action(s); this overstrength factor becomes the design-relevant overstrength factor, defined as $\gamma_{Rd} = \max\{\gamma_{Rd,III}; \gamma_{Rd,II}\}$, in cases where $\mathrm{CoV}[R_d] < \mathrm{CoV}[R_b]$, typical for timber structures designed for controlled yielding and energy dissipation in metal fasteners and fittings.

The overstrength factor $\gamma_{Rd,II}$ depends only on the probabilistic characteristics of $\{R_d; R_b\}$ and the requested safety margin defined by $p_{f,Rd}$. In contrast, $\gamma_{Rd,III}$ depends on all investigated parameters $\{R_d; R_b; G; Q; \alpha\}$ and the safety margin defined by $p_{f,bd}$. Consequently, it is not possible to set a fixed boundary based solely on the difference between $\mathrm{CoV}[R_b]$ and $\mathrm{CoV}[R_d]$ to determine whether the design-relevant overstrength factor $\gamma_{Rd}$ is governed by $\gamma_{Rd,II}$ or $\gamma_{Rd,III}$. However, considering all these parameters would make the process too complex for common design procedures and practical applications, especially as not all relevant information may be generally available. The aim of this paper is to improve the accuracy of the deterministic design approach by simplifying the structural reliability approach within the bounds of current knowledge and general applicability.

To clarify the diffuse transition zone, Table 2 summarises the differences between the overstrength factors $\gamma_{Rd,II}$ and $\gamma_{Rd,III}$ for cases where $\mathrm{CoV}[R_d]$ is close to $\mathrm{CoV}[R_b]$ and the design-relevant overstrength factor $\gamma_{Rd} = \max\{\gamma_{Rd,III}; \gamma_{Rd,II}\}$ is governed by $\gamma_{Rd,II}$. The closer $\mathrm{CoV}[R_d]$ and $\mathrm{CoV}[R_b]$ are, and particularly when $\mathrm{CoV}[R_d] > \mathrm{CoV}[R_b]$ (a more theoretical case), the greater the difference between the two overstrength factors, indicating a clearer dominance of $\gamma_{Rd,II}$ over $\gamma_{Rd,III}$ in the calculation of $\gamma_{Rd}$. This difference also increases as $\{p_{f,Rd}; p_{f,bd}\}$ decrease, i.e. as safety margins increase, because $\gamma_{Rd,II}$ rises faster than $\gamma_{Rd,III}$; see Section 3.1.

For practical applications, with focus on ductility and energy dissipation in metal parts and considering the recommended CoVs in Table A−1 in Annex A with $\mathrm{CoV}[R_{steel}] \leq 7\%$, a $\mathrm{CoV}[R_d] = 15\%$ appears to be of minor relevance and only of interest in very rare cases, even when model uncertainty with $\mathrm{CoV}[X_d] = 10\%$ is taken into account. A similar circumstance can be assumed for semi-ductile failure modes, for example in joints with laterally loaded dowel-type fasteners failing in Johansen's mode two or three, i.e. by one or two plastic hinges per shear plane [44]. Although single fastener failure modes might exhibit variabilities around 15%, their common action in joints leads to capacities with lower variabilities so that for these cases $\mathrm{CoV}[R_d] = 10\%$ appears more appropriate; cf. [45] and [46]. On the other hand, cases featuring variabilities of ductile and brittle capacities in similar range should not be neglected as strength properties of highly homogenised engineered timber construction products such as laminated veneer lumber (LVL), glulam and CLT also partly exhibit variabilities around 10%. Consequently, focusing only on those cases in Table 2 with $\mathrm{CoV}[R_d] = 10\%$, the maximum difference between $\gamma_{Rd,II}$ and $\gamma_{Rd,III}$ amounts to 0.20 for $\{p_{f,Rd}; p_{f,bd}\} = 10^{-1}$ and 0.24 for $\{p_{f,Rd}; p_{f,bd}\} = 10^{-2}$. Including cases with $\mathrm{CoV}[R_d] = 15\%$, the maximum differences become 0.38 for $\{p_{f,Rd}; p_{f,bd}\} = 10^{-1}$ and 0.59 for $\{p_{f,Rd}; p_{f,bd}\} = 10^{-2}$. In both scenarios the maximum values always occur at $\mathrm{CoV}[R_b] = 10\%$. However, the number of cases in Table 2 does not reflect the number of combinations in practice; it is only due to the selection of cases for the paper. The intention of Table 2 is to show the relatively small range of difference between $\gamma_{Rd,II}$ and $\gamma_{Rd,III}$ for the analysed cases.

To apply these findings, along with those from Section 3.1 to typical design procedures commonly used in practice – usually within the LRFD framework – overstrength classes are defined based on the most relevant parameter $\mathrm{CoV}[R_b]$. For designers' guidance, the classes shown in Table 3 are associated with typical brittle capacities of structural timber products, single fasteners and connections. This includes strength-graded and structural timber, as well as laminated structural timber construction products such as glulam, CLT and LVL. The design-relevant overstrength factors $\gamma_{Rd}$ are determined by considering all cases analysed in the parametric study excluding model uncertainty. The overstrength factors $\gamma_{Rd}$ represent the maximum observed values from all analysed cases within each class, thus providing a conservative basis together with soft $\mathrm{CoV}[R_b]$ limits. They are provided separately for $\{p_{f,Rd}; p_{f,bd}\} = \{10^{-1}; 10^{-2}\}$ to offer a range for possible future regulations, considering a fixed value of $p_{f,0} = 10^{-6}$ as common for ultimate limit states in cases of characteristic load cases and a reference period of one year [31]. Additional variations of $p_{f,bd} = 10^{-3}$ and $p_{f,0} = \{10^{-5}; 10^{-7}\}$

**Table 2**
Summary of differences between $\gamma_{Rd,II}$ and $\gamma_{Rd,III}$ ($\gamma_{Rd,II} - \gamma_{Rd,III}$) for $\{p_{f,Rd}; p_{f,bd}\} = \{10^{-1}; 10^{-2}; 10^{-3}\}$ without $X$ for those cases with $\mathrm{CoV}[R_d]$ close to $\mathrm{CoV}[R_b]$ for which the design relevant overstrength factor $\gamma_{Rd}$ is governed by $\gamma_{Rd,II}$.

| | case(s) | CoV $[R_d]$ [%] | CoV $[R_b]$ [%] | $\{p_{f,Rd}; p_{f,bd}\} = 10^{-1}$ | $\{p_{f,Rd}; p_{f,bd}\} = 10^{-2}$ | $\{p_{f,Rd}; p_{f,bd}\} = 10^{-3}$ |
|---|---|---|---|---|---|---|
| $p_{f,0} = 10^{-5}$ | {16} | 10 | 10 | 0.12 | 0.22 | –[a] |
| | {19} | 10 | 15 | –[a] | 0.11 | –[a] |
| | {17} | 15 | 10 | 0.36 | 0.57 | –[a] |
| | {20; 53; 54; 57; 58} | 15 | 15 | 0.13 – 0.23 | 0.26 – 0.47 | –[a] |
| | {23} | 15 | 20 | 0.04 | 0.28 | –[a] |
| | {14; 26; 35; 36; 39; 40; 43; 44} | 15 | 25 | –[a] | 0.06 – 0.14 | –[a] |
| $p_{f,0} = 10^{-6}$ | {16} | 10 | 10 | 0.12 | 0.24 | 0.31 |
| | {19} | 10 | 15 | –[a] | 0.11 | 0.22 |
| | {17} | 15 | 10 | 0.38 | 0.59 | 0.76 |
| | {20; 53; 54; 57; 58} | 15 | 15 | 0.15 – 0.23 | 0.30 – 0.48 | 0.41 – 0.69 |
| | {23} | 15 | 20 | 0.03 | 0.27 | 0.49 |
| | {14; 26; 35; 36; 39; 40; 43; 44} | 15 | 25 | –[a] | 0.03 – 0.14 | 0.27 – 0.32 |
| $p_{f,0} = 10^{-7}$ | {16} | 10 | 10 | 0.13 | 0.24 | –[a] |
| | {19} | 10 | 15 | –[a] | 0.11 | –[a] |
| | {17} | 15 | 10 | 0.39 | 0.61 | –[a] |
| | {20; 53; 54; 57; 58} | 15 | 15 | 0.26 – 0.47 | 0.34 – 0.49 | –[a] |
| | {23} | 15 | 20 | 0.28 | 0.27 | –[a] |
| | {14; 26; 35; 36; 39; 40; 43; 44} | 15 | 25 | 0.06 – 0.14 | 0.03 – 0.14 | –[a] |

[a] $(\gamma_{Rd,II} - \gamma_{Rd,III}) < 0$, i.e. $\gamma_{Rd,III}$ governs the design

**Table 3**
Proposal for classifying the design-relevant overstrength factor $\gamma_{Rd} = \max\{\gamma_{Rd,III}; \gamma_{Rd,II}\}$ in dependency of CoV[$R_b$], $p_{f,Rd}$ and $p_{f,bd}$ for the application within the LRFD framework, based on the conducted parametric study with $\{R_d; R_b\} \sim$ LN but without consideration of the model uncertainty.

| CoV [$R_b$] [%] | examples | $\gamma_{Rd}$ \| $\{p_{f,Rd}; p_{f,bd}\}$ ≤ 0.10 | $\gamma_{Rd}$ \| $\{p_{f,Rd}; p_{f,bd}\}$ ≤ 0.01 |
|---|---|---|---|
| < 10 | specific cases with CoV[$R_d$] close to CoV [$R_b$] | 1.30[1] | 1.40[1] |
| 10 – 20 | strength graded structural timber (compression perpendicular to the grain) structural timber products {glulam; CLT; LVL} (strength properties) single fastener failure modes (embedment strength; withdrawal strength; head pull-through strength) | 1.40[2] | 1.65[2] |
| 20 – 25 | strength graded structural timber (compression parallel to the grain) brittle joint failure modes in timber (block shear; splitting; plug shear) | 1.80[3] | 2.00[2] |
| 25 – 35 | strength graded structural timber (bending; tension parallel & tension perp. to the grain) | 2.45[3] | 2.85[3] |

[1] … governed by $\gamma_{Rd,II}$
[2] … $\gamma_{Rd}$ | CoV[$R_d$] = {5; 10} % governed by $\gamma_{Rd,III}$; $\gamma_{Rd}$ | CoV[$R_d$] = 15% governed by $\gamma_{Rd,II}$
[3] … $\gamma_{Rd}$ | CoV[$R_d$] = {5; 10; 15} % governed by $\gamma_{Rd,III}$

were shown for the selected case studies in Table B−2 and their influences discussed in Section 3.1, while these scenarios were not included in the proposal for classifying the design relevant overstrength factors. To illustrate the selection of the range of parameters, one could rely also on already existing regulations, such as [32], which has since been replaced by [40], which specifies $p_{f,Rd} = 0.04$ (permissible range 0.023–0.067), and which falls between the two boundaries $\{p_{f,Rd}; p_{f,bd}\} = \{10^{-1}; 10^{-2}\}$ selected here. In future discussions on the regulation of overstrength factors in design codes, it should be considered that, based on the findings of this work, which also analyses a wide range of scenarios, the safety margins in relation to $p_{f,Rd}$ and $p_{f,bd}$ need to be agreed upon. This can be achieved by regulating fixed values or, as in [32], by providing permissible ranges and target values.

In addition to the proposed overstrength factors, Table 3 also provides background information on which of the overstrength factors, either $\gamma_{Rd,II}$ or $\gamma_{Rd,III}$, determines $\gamma_{Rd}$. Overall, the maximum values for $\gamma_{Rd,III}$ occur at CoV[$R_d$] = 5% (the lowest investigated variability of ductile capacity), while for $\gamma_{Rd,II}$ they occur at CoV[$R_d$] = 15% (the highest investigated variability of ductile capacity). Furthermore, the proposed overstrength factors increase progressively with increasing CoV[$R_b$]. In literature, focusing on timber connections and overstrength factors formulated according to the LRFD framework, values up to 3.0 are reported in [7], and theoretical values up to 4.0 in [10], with $\gamma_{an}$ up to 2.8 and $\gamma_{sc}$ up to 1.9, and experimental values up to 2.0. However, extreme values up to 4.0 refer to isolated cases, whereas for timber connections a typical range of overstrength factors is 1.2–2.5, depending on connection type, material, and loading direction.

The use of the newly proposed method and overstrength classes can be most easily illustrated by the design of screwed joints (e.g. in connections between main and secondary girders or end-grain joints), where self-tapping screws are used in combination with a steel site-joint (Fig. 4), and particular attention must be given to the hierarchy of failure modes. In such connections, the steel site-joint typically governs the ductile behaviour and may therefore be regarded as the intended fuse element, characterized by a relatively low coefficient of variation (CoV[$R_d$] ≈ 1–5%). On the other hand, several brittle failure mechanisms inherent to timber and self-tapping screws are possible and could be explicitly considered in the overstrength assessment and consequently in design: (i) net-tension failure in glued laminated timber (CoV

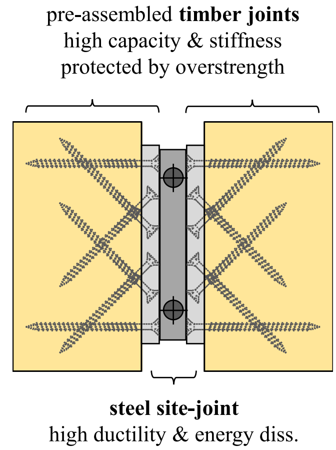


**Fig. 4.** Schematic representation of timber joint with self-tapping, fully threaded screws and outer steel plate in combination with a steel site-joint.

[$R_b$] ≈ 20%), (ii) withdrawal failure of screw groups (CoV[$R_b$] ≈ 10%, which is less than for single fasteners CoV[$R_b$] ≈ 15% due to common group action) and (iii) steel-tension failure of self-tapping screws (CoV ≈ 3–5%). Therefore, to design the timber cross section to prevent the net-tension failure it is possible to compare the design relevant overstrength factors $\gamma_{Rd,I}$ and the newly proposed $\gamma_{Rd} = \max\{\gamma_{Rd,III}; \gamma_{Rd,II}\}$. The most direct comparison to evaluate overstrength is to include only the influence of variability of the ductile (CoV[$R_d$]) and the brittle component(s) (CoV[$R_b$]), which yields to $\gamma_{Rd,I} = \gamma_{SC} \approx 1.18$ and $\gamma_{Rd} = \gamma_{Rd,III} \approx 1.40$ for $\{p_{f,Rd}; p_{f,bd}\} \leq 0.10$; see Table 3. Similarly, for preventing the withdrawal failure of screw groups the proposed overstrength factor is $\gamma_{Rd} = \gamma_{Rd,III} \approx 1.40$ ($\{p_{f,Rd}; p_{f,bd}\} \leq 0.10$). Additional practical guidance for the realisation of such joints, including design and execution rules, is available in Mahlknecht et al. [47], which provides recommendations on minimum geometric and execution requirements for axially loaded groups of screws in hardwood, which are directly applicable in this context and analogously for softwood as well.

A comparable approach applies to tension lap joints, particularly where the outer steel plates in tension between two timber components are again connected by a site-joint with bolts. For moment-resisting connections, such as those encountered in portal frames, similar interaction between ductile and brittle components must again be carefully balanced to ensure a predictable and safe occurrence of the intended failure hierarchy, while the overstrength calculation should reflect the variability of each mechanism accordingly (Table 3).

The proposed overstrength factors in Table 3 are therefore well aligned with the range of reported overstrength factors. However, there are additional contributors to the overstrength factors not included in those listed in Table 3 which may become essential in specific cases or in a more general way, such as $\gamma_M$, $\gamma_{an}$ [1], $\gamma_\eta$ [13,14,16,18], $\gamma_{Rd,yu}$, $\gamma_{cyclic}(n)$ [7] and $\gamma_{err}$ [10]. Some of these additional multipliers, such as $\gamma_{Rd,yu}$ and $\gamma_{cyclic}(n)$, are for a more detailed consideration of ductile behaviour, the multiplier $\gamma_{an}$ accounts for simplified and/or conservative models, whereas multipliers such as $\gamma_\eta$ and $\gamma_{err}$ result from a conservative design and/or discrete cross section dimensions and/or strength classes, and missing or insufficient quality control. Consequently, the final overstrength factors might lead to too high demands on the brittle capacity, i.e. to uneconomic design. To avoid such high overstrength factors, i.e. to remain in the lower classes and find ways to operate with lower variabilities in brittle capacities, the following recommendations are made:

- to design on accidental load cases (the same applies also to characteristic load cases) with sufficient target reliability, strength-graded timber or other materials with a CoV[$R_b$] above 20% should be avoided and replaced with laminated engineered timber construction products, such as glulam, CLT and LVL, which have strength properties with variabilities around 10%, much lower than those typically observed for structural timber strength properties (reducing the influence of $\gamma_M$);

- to design for failure modes of connections that are well described by single-fastener failure modes and to avoid (quasi-)brittle group failure modes; examples of single-fastener failure modes include embedment and yield moment for (primarily) laterally loaded dowel-type fasteners and withdrawal, head-pull through and steel-tension failure for (primarily) axially-loaded dowel-type fasteners; examples of (quasi-)brittle group failure modes include block shear, plug shear, row shear and splitting (reducing the influence of $\gamma_{an}$ and $\gamma_M$);
- to avoid (semi-)ductile failure modes characterised by severe pinching under reverse loading, such as connections with laterally loaded dowel-type fasteners failing in mode two or three according to [44]; these failure modes exhibit greater variability and limited predictability, i.e. model bias and uncertainty in relevant quantities (avoiding the influence of $\gamma_{cyclic}(n)$);
- to direct ductility and energy dissipation to steel (metal) fasteners and fittings, allowing for clear and effective structural designs (for example, well-known yield point, amount of ductility and pre- and post-peak material behaviour) combined with low variabilities in strength properties and overall low model uncertainties (reducing the influence of $\gamma_{an}$);
- to establish quality assurance methods to prevent quality bias between ordered and delivered material quality, particularly regarding steel (metal) qualities; an alternative strategy could involve a method that allows batch-wise adjustment of delivered quality to match the ordered quality by adapting the yield zone, for example, through controlled reduction of the design-relevant diameter of bolts or threaded steel rods; another strategy could be to design for the highest steel classes that still exhibit the desired ductile material behaviour, but typically with less quality bias [30] (reducing or avoiding the influence of $\gamma_{err}$);
- to develop and apply reliable engineering models in combination with clear and not excessively conservative properties in product codes; as properties serve as input parameters for the engineering models any conservativeness adds to model bias (reducing the influence of $\gamma_{an}$);
- to concentrate ductile components in areas of the structures that are of secondary importance, inspectable, maintainable and repairable [4]; the possibility to regularly monitor these areas may also allow for less conservatism;
- reducing $\gamma_\eta$ in practice is challenging due to the limited discrete dimensions of steel fasteners. However, it may be possible to perform batch tests on the delivered materials and adjust the capacity by precisely reducing the cross section (e.g. for glued-in rods, threaded rods etc.) or by localizing yielding in a site joint that is separated from the timber joint. This approach not only reduces $\gamma_\eta$, but also minimises $\gamma_{err}$;
- A value of $\gamma_{Rd,yu} = 1.0$ applies only to ideally plastic materials, which is theoretically possible; however, with careful selection of steel grades, the value can approach 1.0.

In addition to the overstrength factor in Table 3, material partial safety factors, modification factors and similar considerations must be taken into account if the concept is also applied to characteristic load scenarios.

## 4. Conclusions

This study briefly reviews existing definitions of overstrength in timber construction and demonstrates that current design approaches do not always ensure a clear hierarchy between ductile (desired) and brittle (undesired) failure modes. Therefore, a new reliability-based approach is proposed, which explicitly considers the statistical distribution models and coefficients of variation of actions and capacities. The most important results of the parametric study are summarized and concluded in the following:

- To ensure realistic, meaningful and practically relevant input data for the parametric study, a review of recommended statistical distribution models and typical CoVs for representing the random variables was conducted, as this information strongly influences the calculated overstrength factors in the proposed approach.
- The parametric study has shown that different settings for the permanent and variable loads and capacities, particularly their coefficients of variation, strongly influence the calculated overstrength factor. The highest overstrength factors $\gamma_{Rd,III}$ occur when the permanent action dominates (high $\alpha$) in combination with a low CoV[$Q$] and CoV[$R_b$] > CoV[$R_d$]. In contrast, the overstrength factor $\gamma_{Rd,II}$ according to the structural reliability approach is highest when $R_d$ and $R_b$ have similar variabilities.
- Practical recommendations for classifying the design-relevant overstrength factors $\gamma_{Rd} = \max\{\gamma_{Rd,III}; \gamma_{Rd,II}\}$ according to the variability of brittle capacities are provided to assist designers in selecting appropriate values for realistic design scenarios. It is discussed that target reliabilities based on $\{p_{f,Rd}; p_{f,bd}\}$ for avoiding brittle prior to ductile failures should be established during standardization. For timber structures, $\{p_{f,Rd}; p_{f,bd}\}$ in the range of 1–5% appears appropriate, as strengths are more variable compared to steel and because of the limited non-linear response of timber outside zones protected by capacity design (cf. [2]).
- The proposed overstrength classes for target probabilities $\{p_{f,Rd}; p_{f,bd}\} = 10^{-1}$ range from 1.30 to 2.45 and for $\{p_{f,Rd}; p_{f,bd}\} = 10^{-2}$ from 1.40 to 2.85. The classes are defined by ranges of CoV[$R_b$], as dominating parameter for the overstrength factor, and for guidance of the designer linked with class-specific failure modes. The additional analyses with $\{p_{f,Rd}; p_{f,bd}\} = 10^{-3}$ proved relatively high overstrength values which may lead to uneconomical designs.
- In addition to the calculated overstrength factors in this paper, other multipliers as partial overstrength contributors may need to be applied, in particular $\{\gamma_M; \gamma_{an}; \gamma_\eta; \gamma_{Rd,yu}; \gamma_{cyclic}(n); \gamma_{err}\}$. As these additional multipliers may lead to rather high overstrength factors and uneconomical designs, specific design and execution recommendations are provided to ensure that the overstrength factor remains in the lower classes.

As part of future work, it is recommended to extend considerations of ductility and overstrength beyond accidental load scenarios to characteristic load scenarios as a more general design requirement maintaining a clear failure hierarchy. Based on the variation of $p_{f,0}$ performed in this study it can be seen that the influence on overstrength $\gamma_{Rd,III}$ is relatively small – less than a 10% increase if $p_{f,0}$ decreases by a factor of 10, with the change in $\gamma_{Rd,III}$ being proportional to the change in $p_{f,0}$. Furthermore, in principle, the same approach could be applied to avoid excessive plastic deformations or, in general, ductile failure modes in steel-timber joints, for example in dowel-type fasteners such as dowels, bolts, and screws, to facilitate disassembly and reuse in terms of circularity.

In addition, to validate the new approach in a broader and more comprehensive setting, an international test database on fasteners and joints is desirable, including full background information such as test setups and load-displacement curves. Another important aspect is that joints and connections exhibit several different failure modes which, when modelled as a system, each have a specific probability, a circumstance which needs to be considered also in calculating overstrength factors from experimental data.

## CRediT authorship contribution statement

**Boris Azinović:** Writing – review & editing, Investigation, Conceptualization. **Reinhard Brandner:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Boris Azinovic reports financial support was provided by Slovenian National Building and Civil Engineering Institute. Reinhard Brandner reports financial support was provided by Graz University of Technology.

## Acknowledgements

The financial support in the framework of the FFG BRIDGE 1 research project "CLT_joint" (No. 883672) by the Austrian Research Promotion Agency (FFG), Schmid Schrauben Hainfeld GmbH and Technowood AG is thankfully acknowledged. The financial support received from the Slovenian Research Agency (Research Core Funding No. P4–0430 and Research Project No. N2–0280) is also gratefully acknowledged. The work is partially funded also within the TiReX project (ForestValue2 Joint Call 2023) and it has received funding from the European Union's Horizon Europe under grant agreement No. 101094340, a joint call with financing from NFR (Norway), NCN (Poland, grant no. 2023/05/Y/ST8/00176), MICIU (Spain, PCI2024-153432), Ministry of Higher Education, Science and Innovation (MVZI) of the Republic of Slovenia (Slovenia, C3360-24-45201).

## Annex A

**Table A−1**
Summary of recommended statistical distribution models F($Y$), coefficients of variation CoV[$Y$] and bias factors for selected actions and capacities

| random variable $Y$ | stat. distr. model F($Y$) | CoV [$Y$] [%] \| bias | reference |
|---|---|---|---|
| permanent load | N | 5 – 10 (20) | [31,38,48–50] |
| variable load | EV-I; LN; N | ≥ 15 – 50 | [31,49–51] |
| snow load | EV-I (EV-II) | 20 | [38,48,49] |
| wind velocity & pressure | W ($X_{10',mean}$) | 20 – 30 | [38,48,51] |
| | EV-I ($X_{10',mean,max}$) | 25 – 40 | |
| | EV-I ($X_{peak}$) | 10 | |
| self-weight | N | 2.5 (steel)<br>5 (reinf. concrete)<br>10 (constr. timber; glulam) | [48] |
| spectral acceleration | LN | ≥ 50 – 60 | [6,52] |
| material strength | N (summative processes, ductile materials with < CoV) | – | [53] |
| | LN (multiplicative processes) | | |
| | W (brittle materials) | | |
| (reinforced) concrete | LN (compression strength) | 6 – 15 | [48–51] |
| | LN (tension strength) | 30 | |
| | LN (MOE) | 15 | |
| structural steel | LN | 4 ($f_u$)<br>5 – 7 ($f_y$) | [38,48] |
| reinforcing steel | LN; N | 5 | [38,50,51] |
| structural timber | N (compr. perp. strength; density) | 10 | [38,48] |
| | W (tens. perp. strength) | 25 | |
| | LN (bending & shear strength) | 20 – 25 | |
| | LN (tension par. strength) | 30 | |
| | LN (compr. par. strength) | 20 | |
| | LN (MOE; elastic properties) | 13 | |
| glulam | LN (bending strength) | (2) 15 (21) | [38,48,54] |
| | LN (shear strength) | (5) 15 (20) | [55] |
| | LN (MOE; elastic properties) | 3 – 10 | [56] |
| joint failure modes | LN (brittle failure modes of joints with primary laterally-loaded fasteners: block shear; plug shear; row shear; splitting) & (brittle failure modes of joints with primary axially loaded fasteners: withdrawal; screw-tension; head tear-off; splitting; bock shear; rolling shear) | (2) 10 – 25 (30)<br>(2) 5 – 10 (22) | [15] |
| | LN (ductile failure modes of joints with primary laterally-loaded fasteners: yielding of nails, dowels, screws, staples, fittings (angle brackets; hold-downs)) | | |
| fatigue analysis | N; LN; W | – | [53] |
| model uncertainties (actions) | LN; N | 3 – 15 | [48,50,51] |
| model uncertainties (capacities) | LN (concrete compr.) | 14 \| 0.97 | [38,48] |
| | LN (concrete bending) | 7 \| 1.03 | |
| | LN (M & V in frames) | 10 | |
| | LN (steel bend. & shear) | 5 \| 1.15 | |
| | LN (steel welded conn.) | 15 \| 1.15 | |
| | LN (steel bolted conn.) | 15 \| 1.25 | |
| | LN (struct. timber; glulam bending) | 10 \| 1.00 | |

N … normal distribution; LN … lognormal distribution; W … Weibull distribution; EV … extreme value distribution (type not specified); EV-I … extreme value type I distribution (Gumbel); EV-II … extreme value type II distribution (Fréchet)

## Annex B

**Table B-1 (a)**
Main, case specific results from the structural reliability analyses including the overstrength factors $\gamma_{Rd,III}$ and $\gamma_{Rd,II}$ according to [15] and $\gamma_{Rd,II}$ according to approach II for the target failure probabilities $\{p_{f,Rd};\ p_{f,bd}\} = 10^{-1}$ and with / without consideration of the model uncertainty CoV[X] of the ductile ($X_d$) and the brittle part ($X_b$). Please note: the design relevant overstrength factor as max($\gamma_{Rd,III}$; $\gamma_{Rd,II}$) is highlighted in "bold-underlined", the scaling factor $z_d$ refers to $\gamma_{Rd,III}$ and $\gamma_{Rd,II}$, and $z_b$ only to $\gamma_{Rd,III}$

| case | | $\{p_{f,Rd};\ p_{f,bd}\} = 10^{-1}$ with *X* | | | | $\{p_{f,Rd};\ p_{f,bd}\} = 10^{-1}$ without *X* | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $z_b$ | $z_d$ | $\gamma_{Rd,III}$ | $\gamma_{Rd,II}$ | $z_b$ | $z_d$ | $\gamma_{Rd,III}$ | $\gamma_{Rd,II}$ |
| 1 | REF | 4.37 | 2.00 | **1.65** | 1.12 | 3.96 | 1.71 | **1.63** | 1.00 |
| 2 | VG10 | 4.51 | 2.07 | **1.64** | 1.12 | 4.09 | 1.76 | **1.63** | 1.00 |
| 3 | Xdm1.15 | 4.37 | 1.74 | **1.65** | 1.12 | 3.96 | 1.71 | **1.63** | 1.00 |
| 4 | Xdm1.30 | 4.37 | 1.54 | **1.65** | 1.12 | 3.96 | 1.71 | **1.63** | 1.00 |
| 5 | α01VQ30 | 7.65 | 4.21 | **1.37** | 1.12 | 7.12 | 3.87 | **1.29** | 1.00 |
| 6 | α01VQ20 | 6.02 | 3.22 | **1.41** | 1.12 | 5.57 | 2.93 | **1.34** | 1.00 |
| 7 | α01VQ40 | 9.33 | 5.21 | **1.35** | 1.12 | 8.71 | 4.81 | **1.27** | 1.00 |
| 8 | α05VQ30 | 5.52 | 2.90 | **1.44** | 1.12 | 5.09 | 2.62 | **1.37** | 1.00 |
| 9 | α05VQ20 | 4.77 | 2.37 | **1.52** | 1.12 | 4.36 | 2.10 | **1.46** | 1.00 |
| 10 | α05VQ40 | 6.38 | 3.45 | **1.40** | 1.12 | 5.92 | 3.14 | **1.32** | 1.00 |
| 11 | α08VQ20 | 4.26 | 1.85 | **1.73** | 1.12 | 3.84 | 1.52 | **1.78** | 1.00 |
| 12 | α08VQ40 | 4.55 | 2.18 | **1.57** | 1.12 | 4.14 | 1.91 | **1.53** | 1.00 |
| 13 | VRd10VRb25 | 4.37 | 2.22 | **1.56** | 1.20 | 3.96 | 1.92 | **1.58** | 1.10 |
| 14 | VRd15VRb25 | 4.37 | 2.60 | **1.43** | 1.31 | 3.96 | 2.29 | **1.44** | 1.23 |
| 15 | VRd05VRb10 | 2.41 | 2.00 | 1.15 | **1.20** | 2.07 | 1.71 | **1.11** | 1.06 |
| 16 | VRd10VRb10 | 2.41 | 2.22 | 1.09 | **1.29** | 2.07 | 1.92 | 1.08 | **1.20** |
| 17 | VRd15VRb10 | 2.41 | 2.60 | 0.99 | **1.43** | 2.07 | 2.29 | 0.99 | **1.37** |
| 18 | VRd05VRb15 | 2.85 | 2.00 | **1.27** | 1.17 | 2.50 | 1.71 | **1.23** | 1.04 |
| 19 | VRd10VRb15 | 2.85 | 2.22 | 1.20 | **1.26** | 2.50 | 1.92 | **1.19** | 1.16 |
| 20 | VRd15VRb15 | 2.85 | 2.60 | 1.10 | **1.38** | 2.50 | 2.29 | 1.09 | **1.31** |
| 21 | VRd05VRb20 | 3.50 | 2.00 | **1.43** | 1.15 | 3.12 | 1.71 | **1.40** | 1.02 |
| 22 | VRd10VRb20 | 3.50 | 2.22 | **1.36** | 1.23 | 3.12 | 1.92 | **1.36** | 1.13 |
| 23 | VRd15VRb20 | 3.50 | 2.60 | 1.24 | **1.34** | 3.12 | 2.29 | 1.24 | **1.27** |
| 24 | VRd05VRb25 | 4.37 | 2.00 | **1.65** | 1.12 | 3.96 | 1.71 | **1.63** | 1.00 |
| 25 | VRd10VRb25 | 4.37 | 2.22 | **1.56** | 1.20 | 3.96 | 1.92 | **1.58** | 1.10 |
| 26 | VRd15VRb25 | 4.37 | 2.60 | **1.43** | 1.31 | 3.96 | 2.29 | **1.44** | 1.23 |
| 27 | VRd05VRb30 | 5.52 | 2.00 | **1.91** | 1.10 | 5.06 | 1.71 | **1.90** | 0.98 |
| 28 | VRd10VRb30 | 5.52 | 2.22 | **1.81** | 1.17 | 5.06 | 1.92 | **1.84** | 1.08 |
| 29 | VRd15VRb30 | 5.52 | 2.60 | **1.66** | 1.28 | 5.06 | 2.29 | **1.69** | 1.20 |
| 30 | VRd05VRb35 | 7.00 | 2.00 | **2.22** | 1.08 | 6.48 | 1.71 | **2.22** | 0.96 |
| 31 | VRd10VRb35 | 7.00 | 2.22 | **2.10** | 1.15 | 6.48 | 1.92 | **2.15** | 1.06 |
| 32 | VRd15VRb35 | 7.00 | 2.60 | **1.93** | 1.25 | 6.48 | 2.29 | **1.97** | 1.18 |
| 33 | VQ20α08VRd10VRb25 | 4.26 | 2.10 | **1.61** | 1.20 | 3.84 | 1.77 | **1.66** | 1.10 |
| 34 | VQ40α08VRd10VRb25 | 4.55 | 2.39 | **1.51** | 1.20 | 4.14 | 2.11 | **1.50** | 1.10 |
| 35 | VQ20α08VRd15VRb25 | 4.26 | 2.50 | **1.45** | 1.31 | 3.84 | 2.18 | **1.48** | 1.23 |
| 36 | VQ40α08VRd15VRb25 | 4.55 | 2.75 | **1.41** | 1.31 | 4.14 | 2.46 | **1.41** | 1.23 |
| 37 | VQ20α01VRd10VRb25 | 6.02 | 3.45 | **1.39** | 1.20 | 5.57 | 3.15 | **1.36** | 1.10 |
| 38 | VQ40α01VRd10VRb25 | 9.33 | 5.52 | **1.34** | 1.20 | 8.71 | 5.11 | **1.31** | 1.10 |
| 39 | VQ20α01VRd15VRb25 | 6.02 | 3.83 | **1.34** | 1.31 | 5.57 | 3.52 | **1.32** | 1.23 |
| 40 | VQ40α01VRd15VRb25 | 9.33 | 6.03 | **1.32** | 1.31 | 8.71 | 5.61 | **1.30** | 1.23 |
| 41 | VQ20α05VRd10VRb25 | 4.77 | 2.58 | **1.47** | 1.20 | 4.36 | 2.30 | **1.45** | 1.10 |
| 42 | VQ40α05VRd10VRb25 | 6.38 | 3.68 | **1.38** | 1.20 | 5.92 | 3.37 | **1.35** | 1.10 |
| 43 | VQ20α05VRd15VRb25 | 4.77 | 2.93 | **1.38** | 1.31 | 4.36 | 2.64 | **1.38** | 1.23 |
| 44 | VQ40α05VRd15VRb25 | 6.38 | 4.07 | **1.33** | 1.31 | 5.92 | 3.75 | **1.32** | 1.23 |
| 45 | VQ20α08VRd05VRb15 | 2.72 | 1.85 | **1.30** | 1.17 | 2.34 | 1.52 | **1.30** | 1.04 |
| 46 | VQ40α08VRd05VRb15 | 3.05 | 2.18 | **1.24** | 1.17 | 2.71 | 1.91 | **1.19** | 1.04 |
| 47 | VQ20α08VRd05VRb35 | 6.87 | 1.85 | **2.35** | 1.08 | 6.36 | 1.52 | **2.45** | 0.96 |
| 48 | VQ40α08VRd05VRb35 | 7.18 | 2.18 | **2.09** | 1.08 | 6.66 | 1.91 | **2.05** | 0.96 |
| 49 | VQ20α01VRd05VRb15 | 4.39 | 3.22 | **1.21** | 1.17 | 4.00 | 2.93 | **1.15** | 1.04 |
| 50 | VQ40α01VRd05VRb15 | 7.07 | 5.21 | **1.20** | 1.17 | 6.52 | 4.81 | **1.14** | 1.04 |
| 51 | VQ20α01VRd05VRb35 | 8.88 | 3.22 | **1.75** | 1.08 | 8.31 | 2.93 | **1.66** | 0.96 |
| 52 | VQ40α01VRd05VRb35 | 13.16 | 5.21 | **1.60** | 1.08 | 12.41 | 4.81 | **1.51** | 0.96 |
| 53 | VQ20α08VRd15VRb15 | 2.72 | 2.50 | 1.09 | **1.38** | 2.34 | 2.18 | 1.08 | **1.31** |
| 54 | VQ40α08VRd15VRb15 | 3.05 | 2.75 | 1.11 | **1.38** | 2.71 | 2.46 | 1.10 | **1.31** |
| 55 | VQ20α08VRd15VRb35 | 6.87 | 2.50 | **1.97** | 1.25 | 6.36 | 2.18 | **2.04** | 1.18 |
| 56 | VQ40α08VRd15VRb35 | 7.18 | 2.75 | **1.87** | 1.25 | 6.66 | 2.46 | **1.89** | 1.18 |
| 57 | VQ20α01VRd15VRb15 | 4.39 | 3.83 | 1.15 | **1.38** | 4.00 | 3.52 | 1.14 | **1.31** |
| 58 | VQ40α01VRd15VRb15 | 7.07 | 6.03 | 1.17 | **1.38** | 6.52 | 5.61 | 1.16 | **1.31** |
| 59 | VQ20α01VRd15VRb35 | 8.88 | 3.83 | **1.66** | 1.25 | 8.31 | 3.52 | **1.65** | 1.18 |
| 60 | VQ40α01VRd15VRb35 | 13.16 | 6.03 | **1.56** | 1.25 | 12.41 | 5.61 | **1.54** | 1.18 |

**Table B-1 (b)**

Main, case specific results from the structural reliability analyses including the overstrength factors $\gamma_{Rd,III}$ and $\gamma_{Rd,II}$ according to [15], $\gamma_{Rd,I}$ according to [1] representing approach I and $\gamma_{Rd,II}$ according to approach II for two different settings of the target failure probabilities $\{p_{f,Rd}; p_{f,bd}\} = 10^{-2}$ and with / without consideration of the model uncertainty CoV[X] of the ductile ($X_d$) and the brittle part ($X_b$). Please note: the design relevant overstrength factor as max($\gamma_{Rd,III}$; $\gamma_{Rd,II}$) is highlighted in "bold-underlined", the scaling factor $z_d$ refers to $\gamma_{Rd,III}$ and $\gamma_{Rd,II}$, and $z_b$ only to $\gamma_{Rd,III}$

| | | $\{p_{f,Rd}; p_{f,bd}\} = 10^{-2}$ with $X$ | | | | | $\{p_{f,Rd}; p_{f,bd}\} = 10^{-2}$ without $X$ | | | | with $X$ | without $X$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| case | | $\gamma_{Rd,II}$ | $z_b$ | $z_d$ | $\gamma_{Rd,III}$ | $\gamma_{Rd,II}$ | $z_b$ | $z_d$ | $\gamma_{Rd,III}$ | $\gamma_{Rd,II}$ | $\gamma_{Rd,I}$ | $\gamma_{Rd,I}$ |
| 1 | REF | 1.00 | 4.91 | 2.00 | **1.85** | 1.52 | 4.42 | 1.71 | **1.82** | 1.30 | 1.44 | 1.18 |
| 2 | VG10 | 1.00 | 5.08 | 2.07 | **1.85** | 1.52 | 4.57 | 1.76 | **1.82** | 1.30 | 1.44 | 1.18 |
| 3 | Xdm1.15 | 1.00 | 4.91 | 1.74 | **1.85** | 1.52 | 4.42 | 1.71 | **1.82** | 1.30 | 1.44 | 1.18 |
| 4 | Xdm1.30 | 1.00 | 4.91 | 1.54 | **1.85** | 1.52 | 4.42 | 1.71 | **1.82** | 1.30 | 1.44 | 1.18 |
| 5 | α01VQ30 | 1.00 | 8.99 | 4.21 | **1.61** | 1.52 | 8.32 | 3.87 | **1.51** | 1.30 | 1.44 | 1.18 |
| 6 | α01VQ20 | 1.00 | 7.00 | 3.22 | **1.64** | 1.52 | 6.44 | 2.93 | **1.55** | 1.30 | 1.44 | 1.18 |
| 7 | α01VQ40 | 1.00 | 11.05 | 5.21 | **1.60** | 1.52 | 10.26 | 4.81 | **1.50** | 1.30 | 1.44 | 1.18 |
| 8 | α05VQ30 | 1.00 | 6.38 | 2.90 | **1.66** | 1.52 | 5.85 | 2.62 | **1.57** | 1.30 | 1.44 | 1.18 |
| 9 | α05VQ20 | 1.00 | 5.43 | 2.37 | **1.72** | 1.52 | 4.93 | 2.10 | **1.65** | 1.30 | 1.44 | 1.18 |
| 10 | α05VQ40 | 1.00 | 7.44 | 3.45 | **1.63** | 1.52 | 6.86 | 3.14 | **1.53** | 1.30 | 1.44 | 1.18 |
| 11 | α08VQ20 | 1.00 | 4.77 | 1.85 | **1.94** | 1.52 | 4.27 | 1.52 | **1.97** | 1.30 | 1.44 | 1.18 |
| 12 | α08VQ40 | 1.00 | 5.14 | 2.18 | **1.78** | 1.52 | 4.65 | 1.91 | **1.72** | 1.30 | 1.44 | 1.18 |
| 13 | VRd10VRb25 | 1.10 | 4.91 | 2.22 | **1.76** | 1.64 | 4.42 | 1.92 | **1.76** | 1.46 | 1.59 | 1.39 |
| 14 | VRd15VRb25 | 1.23 | 4.91 | 2.60 | 1.61 | **1.83** | 4.42 | 2.29 | 1.61 | **1.67** | 1.80 | 1.63 |
| 15 | VRd05VRb10 | 1.06 | 2.61 | 2.00 | 1.24 | **1.45** | 2.22 | 1.71 | **1.19** | 1.19 | 1.44 | 1.18 |
| 16 | VRd10VRb10 | **1.20** | 2.61 | 2.22 | 1.17 | **1.59** | 2.22 | 1.92 | 1.15 | **1.39** | 1.59 | 1.39 |
| 17 | VRd15VRb10 | **1.37** | 2.61 | 2.60 | 1.08 | **1.81** | 2.22 | 2.29 | 1.06 | **1.65** | 1.80 | 1.63 |
| 18 | VRd05VRb15 | 1.04 | 3.12 | 2.00 | 1.38 | **1.46** | 2.70 | 1.71 | **1.33** | 1.22 | 1.44 | 1.18 |
| 19 | VRd10VRb15 | 1.16 | 3.12 | 2.22 | 1.31 | **1.60** | 2.70 | 1.92 | 1.29 | **1.40** | 1.59 | 1.39 |
| 20 | VRd15VRb15 | **1.31** | 3.12 | 2.60 | 1.20 | **1.80** | 2.70 | 2.29 | 1.18 | **1.63** | 1.80 | 1.63 |
| 21 | VRd05VRb20 | 1.02 | 3.87 | 2.00 | **1.59** | 1.49 | 3.42 | 1.71 | **1.54** | 1.26 | 1.44 | 1.18 |
| 22 | VRd10VRb20 | 1.13 | 3.87 | 2.22 | 1.50 | **1.61** | 3.42 | 1.92 | **1.49** | 1.43 | 1.59 | 1.39 |
| 23 | VRd15VRb20 | **1.27** | 3.87 | 2.60 | 1.38 | **1.81** | 3.42 | 2.29 | 1.37 | **1.64** | 1.80 | 1.63 |
| 24 | VRd05VRb25 | 1.00 | 4.91 | 2.00 | **1.85** | 1.52 | 4.42 | 1.71 | **1.82** | 1.30 | 1.44 | 1.18 |
| 25 | VRd10VRb25 | 1.10 | 4.91 | 2.22 | **1.76** | 1.64 | 4.42 | 1.92 | **1.76** | 1.46 | 1.59 | 1.39 |
| 26 | VRd15VRb25 | 1.23 | 4.91 | 2.60 | 1.61 | **1.83** | 4.42 | 2.29 | 1.61 | **1.67** | 1.80 | 1.63 |
| 27 | VRd05VRb30 | 0.98 | 6.31 | 2.00 | **2.18** | 1.55 | 5.74 | 1.71 | **2.16** | 1.34 | 1.44 | 1.18 |
| 28 | VRd10VRb30 | 1.08 | 6.31 | 2.22 | **2.07** | 1.67 | 5.74 | 1.92 | **2.09** | 1.50 | 1.59 | 1.39 |
| 29 | VRd15VRb30 | 1.20 | 6.31 | 2.60 | **1.90** | 1.86 | 5.74 | 2.29 | **1.91** | 1.70 | 1.80 | 1.63 |
| 30 | VRd05VRb35 | 0.96 | 8.13 | 2.00 | **2.58** | 1.59 | 7.49 | 1.71 | **2.57** | 1.38 | 1.44 | 1.18 |
| 31 | VRd10VRb35 | 1.06 | 8.13 | 2.22 | **2.45** | 1.71 | 7.49 | 1.92 | **2.49** | 1.54 | 1.59 | 1.39 |
| 32 | VRd15VRb35 | 1.18 | 8.13 | 2.60 | **2.24** | 1.89 | 7.49 | 2.29 | **2.28** | 1.73 | 1.80 | 1.63 |
| 33 | VQ20α08VRd10VRb25 | 1.10 | 4.77 | 2.10 | **1.80** | 1.64 | 4.27 | 1.77 | **1.85** | 1.46 | 1.59 | 1.39 |
| 34 | VQ40α08VRd10VRb25 | 1.10 | 5.14 | 2.39 | **1.71** | 1.64 | 4.65 | 2.11 | **1.69** | 1.46 | 1.59 | 1.39 |
| 35 | VQ20α08VRd15VRb25 | 1.23 | 4.77 | 2.50 | 1.63 | **1.83** | 4.27 | 2.18 | 1.64 | **1.67** | 1.80 | 1.63 |
| 36 | VQ40α08VRd15VRb25 | 1.23 | 5.14 | 2.75 | 1.59 | **1.83** | 4.65 | 2.46 | 1.58 | **1.67** | 1.80 | 1.63 |
| 37 | VQ20α01VRd10VRb25 | 1.10 | 7.00 | 3.45 | 1.61 | **1.64** | 6.44 | 3.15 | **1.57** | 1.46 | 1.59 | 1.39 |
| 38 | VQ40α01VRd10VRb25 | 1.10 | 11.05 | 5.52 | 1.59 | **1.64** | 10.26 | 5.11 | **1.54** | 1.46 | 1.59 | 1.39 |
| 39 | VQ20α01VRd15VRb25 | 1.23 | 7.00 | 3.83 | 1.56 | **1.83** | 6.44 | 3.52 | 1.53 | **1.67** | 1.80 | 1.63 |
| 40 | VQ40α01VRd15VRb25 | 1.23 | 11.05 | 6.03 | 1.56 | **1.83** | 10.26 | 5.61 | 1.53 | **1.67** | 1.80 | 1.63 |
| 41 | VQ20α05VRd10VRb25 | 1.10 | 5.43 | 2.58 | **1.67** | 1.64 | 4.93 | 2.30 | **1.64** | 1.46 | 1.59 | 1.39 |
| 42 | VQ40α05VRd10VRb25 | 1.10 | 7.44 | 3.68 | 1.61 | **1.64** | 6.86 | 3.37 | **1.56** | 1.46 | 1.59 | 1.39 |
| 43 | VQ20α05VRd15VRb25 | 1.23 | 5.43 | 2.93 | 1.58 | **1.83** | 4.93 | 2.64 | 1.56 | **1.67** | 1.80 | 1.63 |
| 44 | VQ40α05VRd15VRb25 | 1.23 | 7.44 | 4.07 | 1.56 | **1.83** | 6.86 | 3.75 | 1.53 | **1.67** | 1.80 | 1.63 |
| 45 | VQ20α08VRd05VRb15 | 1.04 | 2.95 | 1.85 | 1.41 | **1.46** | 2.51 | 1.52 | **1.39** | 1.22 | 1.44 | 1.18 |
| 46 | VQ40α08VRd05VRb15 | 1.04 | 3.37 | 2.18 | 1.37 | **1.46** | 2.96 | 1.91 | **1.31** | 1.22 | 1.44 | 1.18 |
| 47 | VQ20α08VRd05VRb35 | 0.96 | 7.97 | 1.85 | **2.73** | 1.59 | 7.33 | 1.52 | **2.83** | 1.38 | 1.44 | 1.18 |
| 48 | VQ40α08VRd05VRb35 | 0.96 | 8.38 | 2.18 | **2.44** | 1.59 | 7.73 | 1.91 | **2.38** | 1.38 | 1.44 | 1.18 |
| 49 | VQ20α01VRd05VRb15 | 1.04 | 4.97 | 3.22 | 1.37 | **1.46** | 4.50 | 2.93 | **1.29** | 1.22 | 1.44 | 1.18 |
| 50 | VQ40α01VRd05VRb15 | 1.04 | 8.16 | 5.21 | 1.39 | **1.46** | 7.47 | 4.81 | **1.31** | 1.22 | 1.44 | 1.18 |
| 51 | VQ20α01VRd05VRb35 | 0.96 | 10.61 | 3.22 | **2.09** | 1.59 | 9.88 | 2.93 | **1.98** | 1.38 | 1.44 | 1.18 |
| 52 | VQ40α01VRd05VRb35 | 0.96 | 16.05 | 5.21 | **1.95** | 1.59 | 15.06 | 4.81 | **1.83** | 1.38 | 1.44 | 1.18 |
| 53 | VQ20α08VRd15VRb15 | **1.31** | 2.95 | 2.50 | 1.18 | **1.80** | 2.51 | 2.18 | 1.15 | **1.63** | 1.80 | 1.63 |
| 54 | VQ40α08VRd15VRb15 | **1.31** | 3.37 | 2.75 | 1.22 | **1.80** | 2.96 | 2.46 | 1.20 | **1.63** | 1.80 | 1.63 |
| 55 | VQ20α08VRd15VRb35 | 1.18 | 7.97 | 2.50 | **2.29** | 1.89 | 7.33 | 2.18 | **2.35** | 1.73 | 1.80 | 1.63 |
| 56 | VQ40α08VRd15VRb35 | 1.18 | 8.38 | 2.75 | **2.18** | 1.89 | 7.73 | 2.46 | **2.19** | 1.73 | 1.80 | 1.63 |
| 57 | VQ20α01VRd15VRb15 | **1.31** | 4.97 | 3.83 | 1.30 | **1.80** | 4.50 | 3.52 | 1.28 | **1.63** | 1.80 | 1.63 |
| 58 | VQ40α01VRd15VRb15 | **1.31** | 8.16 | 6.03 | 1.35 | **1.80** | 7.47 | 5.61 | 1.33 | **1.63** | 1.80 | 1.63 |
| 59 | VQ20α01VRd15VRb35 | 1.18 | 10.61 | 3.83 | **1.98** | 1.89 | 9.88 | 3.52 | **1.96** | 1.73 | 1.80 | 1.63 |
| 60 | VQ40α01VRd15VRb35 | 1.18 | 16.05 | 6.03 | **1.91** | 1.89 | 15.06 | 5.61 | **1.87** | 1.73 | 1.80 | 1.63 |

**Table B-2 (a)**

Results from the structural reliability analyses for overstrength factors $\gamma_{Rd,III}$ and $\gamma_{Rd,II}$ including additional cases with target failure probability $\{p_{f,Rd}; p_{f,bd}\} = 10^{-3}$ and additional cases with $p_{f,0} = \{10^{-5}; 10^{-6}\}$ in pair with target failure probabilities $\{p_{f,Rd}; p_{f,bd}\} = \{10^{-1}; 10^{-2}; 10^{-3}\}$. The results do not include the model uncertainty CoV [X] of the ductile ($X_d$) and the brittle part ($X_b$). Please note: the design relevant overstrength factor as max($\gamma_{Rd,III}$; $\gamma_{Rd,II}$) is highlighted in "bold-underlined", the scaling factor $z_d$ refers to $\gamma_{Rd,III}$ and $\gamma_{Rd,II}$, and $z_b$ only to $\gamma_{Rd,III}$

| case | | $p_{f,0} = 10^{-5}$ $\{p_{f,Rd}; p_{f,bd}\} = 10^{-1}$ | | | | $p_{f,0} = 10^{-5}$ $\{p_{f,Rd}; p_{f,bd}\} = 10^{-2}$ | | | | $p_{f,0} = 10^{-6}$ $\{p_{f,Rd}; p_{f,bd}\} = 10^{-3}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $z_b$ | $z_d$ | $\gamma_{Rd,III}$ | $\gamma_{Rd,II}$ | $z_b$ | $z_d$ | $\gamma_{Rd,III}$ | $\gamma_{Rd,II}$ | $z_b$ | $z_d$ | $\gamma_{Rd,III}$ | $\gamma_{Rd,II}$ |
| 1 | REF | 3.52 | 1.59 | **1.56** | 1.00 | 3.96 | 1.59 | **1.75** | 1.30 | 4.89 | 1.71 | **2.02** | 1.57 |
| 2 | VG10 | 3.63 | 1.65 | **1.55** | 1.00 | 4.09 | 1.65 | **1.75** | 1.30 | 5.07 | 1.76 | **2.02** | 1.57 |
| 3 | Xdm1.15 | 3.52 | 1.59 | **1.56** | 1.00 | 3.96 | 1.59 | **1.75** | 1.30 | 4.89 | 1.71 | **2.02** | 1.57 |
| 4 | Xdm1.30 | 3.52 | 1.59 | **1.56** | 1.00 | 3.96 | 1.59 | **1.75** | 1.30 | 4.89 | 1.71 | **2.02** | 1.57 |
| 5 | α01VQ30 | 6.00 | 3.37 | **1.25** | 1.00 | 7.12 | 3.37 | **1.49** | 1.30 | 9.62 | 3.87 | **1.75** | 1.57 |
| 6 | α01VQ20 | 4.77 | 2.59 | **1.29** | 1.00 | 5.57 | 2.59 | **1.51** | 1.30 | 7.37 | 2.93 | **1.77** | 1.57 |
| 7 | α01VQ40 | 7.28 | 4.14 | **1.24** | 1.00 | 8.71 | 4.14 | **1.48** | 1.30 | 11.92 | 4.81 | **1.74** | 1.57 |
| 8 | α05VQ30 | 4.39 | 2.34 | **1.32** | 1.00 | 5.09 | 2.34 | **1.53** | 1.30 | 6.65 | 2.62 | **1.79** | 1.57 |
| 9 | α05VQ20 | 3.82 | 1.91 | **1.40** | 1.00 | 4.36 | 1.91 | **1.60** | 1.30 | 5.54 | 2.10 | **1.85** | 1.57 |
| 10 | α05VQ40 | 5.04 | 2.77 | **1.28** | 1.00 | 5.92 | 2.77 | **1.50** | 1.30 | 7.86 | 3.14 | **1.76** | 1.57 |
| 11 | α08VQ20 | 3.43 | 1.44 | **1.67** | 1.00 | 3.84 | 1.44 | **1.87** | 1.30 | 4.71 | 1.52 | **2.18** | 1.57 |
| 12 | α08VQ40 | 3.65 | 1.75 | **1.47** | 1.00 | 4.14 | 1.75 | **1.66** | 1.46 | 5.19 | 1.91 | **1.91** | 1.57 |
| 13 | VRd10VRb25 | 3.52 | 1.78 | **1.51** | 1.10 | 3.96 | 1.78 | **1.70** | 1.67 | 4.89 | 1.92 | **1.95** | 1.79 |
| 14 | VRd15VRb25 | 3.52 | 2.09 | **1.40** | 1.23 | 3.96 | 2.09 | **1.58** | 1.19 | 4.89 | 2.29 | 1.79 | **2.08** |
| 15 | VRd05VRb10 | 1.92 | 1.59 | **1.11** | 1.06 | 2.07 | 1.59 | 1.20 | **1.39** | 2.37 | 1.71 | 1.28 | **1.30** |
| 16 | VRd10VRb10 | 1.92 | 1.78 | 1.08 | **1.20** | 2.07 | 1.78 | 1.16 | **1.65** | 2.37 | 1.92 | 1.23 | **1.55** |
| 17 | VRd15VRb10 | 1.92 | 2.09 | 1.00 | **1.37** | 2.07 | 2.09 | 1.08 | **1.22** | 2.37 | 2.29 | 1.13 | **1.89** |
| 18 | VRd05VRb15 | 2.29 | 1.59 | **1.21** | 1.04 | 2.50 | 1.59 | 1.32 | **1.40** | 2.92 | 1.71 | **1.44** | 1.38 |
| 19 | VRd10VRb15 | 2.29 | 1.78 | **1.18** | 1.16 | 2.50 | 1.78 | 1.28 | **1.63** | 2.92 | 1.92 | 1.39 | **1.61** |
| 20 | VRd15VRb15 | 2.29 | 2.09 | 1.09 | **1.31** | 2.50 | 2.09 | 1.19 | **1.26** | 2.92 | 2.29 | 1.27 | **1.92** |
| 21 | VRd05VRb20 | 2.82 | 1.59 | **1.36** | 1.02 | 3.12 | 1.59 | **1.51** | 1.43 | 3.74 | 1.71 | **1.68** | 1.47 |
| 22 | VRd10VRb20 | 2.82 | 1.78 | **1.33** | 1.13 | 3.12 | 1.78 | 1.47 | **1.64** | 3.74 | 1.92 | 1.63 | **1.69** |
| 23 | VRd15VRb20 | 2.82 | 2.09 | 1.23 | **1.27** | 3.12 | 2.09 | **1.36** | 1.30 | 3.74 | 2.29 | 1.49 | **1.99** |
| 24 | VRd05VRb25 | 3.52 | 1.59 | **1.56** | 1.00 | 3.96 | 1.59 | **1.75** | 1.46 | 4.89 | 1.71 | **2.02** | 1.57 |
| 25 | VRd10VRb25 | 3.52 | 1.78 | **1.51** | 1.10 | 3.96 | 1.78 | **1.70** | 1.67 | 4.89 | 1.92 | **1.95** | 1.79 |
| 26 | VRd15VRb25 | 3.52 | 2.09 | **1.40** | 1.23 | 3.96 | 2.09 | **1.58** | 1.34 | 4.89 | 2.29 | 1.79 | **2.08** |
| 27 | VRd05VRb30 | 4.41 | 1.59 | **1.78** | 0.98 | 5.06 | 1.59 | **2.04** | 1.50 | 6.47 | 1.71 | **2.43** | 1.68 |
| 28 | VRd10VRb30 | 4.41 | 1.78 | **1.74** | 1.08 | 5.06 | 1.78 | **1.99** | 1.70 | 6.47 | 1.92 | **2.35** | 1.90 |
| 29 | VRd15VRb30 | 4.41 | 2.09 | **1.61** | 1.20 | 5.06 | 2.09 | **1.84** | 1.38 | 6.47 | 2.29 | 2.16 | **2.18** |
| 30 | VRd05VRb35 | 5.54 | 1.59 | **2.04** | 0.96 | 6.48 | 1.59 | **2.39** | 1.54 | 8.58 | 1.71 | **2.94** | 1.79 |
| 31 | VRd10VRb35 | 5.54 | 1.78 | **1.99** | 1.06 | 6.48 | 1.78 | **2.33** | 1.73 | 8.58 | 1.92 | **2.85** | 2.01 |
| 32 | VRd15VRb35 | 5.54 | 2.09 | **1.84** | 1.18 | 6.48 | 2.09 | **2.16** | 1.46 | 8.58 | 2.29 | **2.61** | 2.30 |
| 33 | VQ20α08VRd10VRb25 | 3.43 | 1.66 | **1.58** | 1.10 | 3.84 | 1.66 | **1.77** | 1.46 | 4.71 | 1.77 | **2.04** | 1.79 |
| 34 | VQ40α08VRd10VRb25 | 3.65 | 1.93 | **1.45** | 1.10 | 4.14 | 1.93 | 1.65 | **1.67** | 5.19 | 2.11 | **1.88** | 1.79 |
| 35 | VQ20α08VRd15VRb25 | 3.43 | 2.01 | **1.43** | 1.23 | 3.84 | 2.01 | 1.60 | **1.67** | 4.71 | 2.18 | 1.81 | **2.08** |
| 36 | VQ40α08VRd15VRb25 | 3.66 | 2.22 | **1.38** | 1.23 | 4.14 | 2.22 | **1.56** | 1.46 | 5.19 | 2.46 | 1.76 | **2.08** |
| 37 | VQ20α01VRd10VRb25 | 4.77 | 2.76 | **1.32** | 1.10 | 5.57 | 2.76 | **1.55** | 1.46 | 7.37 | 3.15 | **1.79** | 1.79 |
| 38 | VQ40α01VRd10VRb25 | 7.28 | 4.36 | **1.28** | 1.10 | 8.71 | 4.36 | **1.53** | 1.67 | 11.92 | 5.11 | **1.79** | 1.79 |
| 39 | VQ20α01VRd15VRb25 | 4.77 | 3.05 | **1.31** | 1.23 | 5.57 | 3.05 | 1.53 | **1.67** | 7.37 | 3.52 | 1.75 | **2.08** |
| 40 | VQ40α01VRd15VRb25 | 7.28 | 4.74 | **1.29** | 1.23 | 8.71 | 4.74 | **1.54** | 1.46 | 11.92 | 5.61 | 1.78 | **2.08** |
| 41 | VQ20α05VRd10VRb25 | 3.82 | 2.08 | **1.41** | 1.10 | 4.36 | 2.08 | **1.61** | 1.46 | 5.54 | 2.30 | **1.84** | 1.79 |
| 42 | VQ40α05VRd10VRb25 | 5.04 | 2.94 | **1.31** | 1.10 | 5.92 | 2.94 | 1.54 | **1.67** | 7.86 | 3.37 | **1.79** | 1.79 |
| 43 | VQ20α05VRd15VRb25 | 3.82 | 2.36 | **1.35** | 1.23 | 4.36 | 2.36 | 1.54 | **1.67** | 5.54 | 2.64 | 1.75 | **2.08** |
| 44 | VQ40α05VRd15VRb25 | 5.04 | 3.24 | **1.30** | 1.23 | 5.92 | 3.24 | **1.53** | 1.22 | 7.86 | 3.75 | 1.75 | **2.08** |
| 45 | VQ20α08VRd05VRb15 | 2.18 | 1.44 | **1.27** | 1.04 | 2.34 | 1.44 | **1.37** | 1.22 | 2.68 | 1.52 | **1.48** | 1.38 |
| 46 | VQ40α08VRd05VRb15 | 2.46 | 1.75 | **1.18** | 1.04 | 2.71 | 1.75 | 1.30 | **1.38** | 3.23 | 1.91 | **1.42** | 1.38 |
| 47 | VQ20α08VRd05VRb35 | 5.45 | 1.44 | **2.22** | 0.96 | 6.36 | 1.44 | **2.59** | 1.38 | 8.38 | 1.52 | **3.23** | 1.79 |
| 48 | VQ40α08VRd05VRb35 | 5.67 | 1.75 | **1.90** | 0.96 | 6.66 | 1.75 | **2.23** | 1.22 | 8.89 | 1.91 | **2.73** | 1.79 |
| 49 | VQ20α01VRd05VRb15 | 3.52 | 2.59 | **1.14** | 1.04 | 4.00 | 2.59 | **1.30** | 1.22 | 5.02 | 2.93 | **1.44** | 1.38 |
| 50 | VQ40α01VRd05VRb15 | 5.61 | 4.14 | **1.14** | 1.04 | 6.52 | 4.14 | 1.32 | **1.38** | 8.45 | 4.81 | **1.48** | 1.38 |
| 51 | VQ20α01VRd05VRb35 | 6.90 | 2.59 | **1.56** | 0.96 | 8.31 | 2.59 | **1.88** | 1.38 | 11.62 | 2.93 | **2.33** | 1.79 |
| 52 | VQ40α01VRd05VRb35 | 10.05 | 4.14 | **1.42** | 0.96 | 12.41 | 4.14 | **1.76** | 1.63 | 18.02 | 4.81 | **2.19** | 1.79 |
| 53 | VQ20α08VRd15VRb15 | 2.18 | 2.01 | 1.08 | **1.31** | 2.34 | 2.01 | 1.17 | **1.63** | 2.68 | 2.18 | 1.23 | **1.92** |
| 54 | VQ40α08VRd15VRb15 | 2.46 | 2.22 | 1.11 | **1.31** | 2.71 | 2.22 | 1.22 | **1.73** | 3.23 | 2.46 | 1.31 | **1.92** |
| 55 | VQ20α08VRd15VRb35 | 5.45 | 2.01 | **1.89** | 1.18 | 6.36 | 2.01 | **2.21** | 1.73 | 8.38 | 2.18 | **2.69** | 2.30 |
| 56 | VQ40α08VRd15VRb35 | 5.67 | 2.22 | **1.78** | 1.18 | 6.66 | 2.22 | **2.09** | 1.63 | 8.89 | 2.46 | **2.52** | 2.30 |
| 57 | VQ20α01VRd15VRb15 | 3.52 | 3.05 | 1.15 | **1.31** | 4.00 | 3.05 | 1.31 | **1.63** | 5.02 | 3.52 | 1.43 | **1.92** |
| 58 | VQ40α01VRd15VRb15 | 5.61 | 4.74 | 1.19 | **1.31** | 6.52 | 4.74 | 1.38 | **1.73** | 8.45 | 5.61 | 1.51 | **1.92** |
| 59 | VQ20α01VRd15VRb35 | 6.90 | 3.05 | 1.58 | 1.18 | 8.31 | 3.05 | **1.90** | 1.73 | 11.62 | 3.52 | **2.30** | 2.30 |
| 60 | VQ40α01VRd15VRb35 | 10.05 | 4.74 | **1.48** | 1.18 | 12.41 | 4.74 | **1.83** | 1.30 | 18.02 | 5.61 | 2.24 | **2.30** |

**Table B-2 (b)**

Results from the structural reliability analyses for overstrength factors $\gamma_{Rd,III}$ and $\gamma_{Rd,II}$ including additional cases with target failure probability $\{p_{f,Rd}; p_{f,bd}\} = 10^{-3}$ and additional cases with $p_{f,0} = 10^{-7}$ in pair with target failure probabilities $\{p_{f,Rd}; p_{f,bd}\} = \{10^{-1}; 10^{-2}\}$. The results do not include the model uncertainty CoV[X] of the ductile ($X_d$) and the brittle part ($X_b$). Please note: the design relevant overstrength factor as max($\gamma_{Rd,III}$; $\gamma_{Rd,II}$) is highlighted in "bold-underlined", the scaling factor $z_d$ refers to $\gamma_{Rd,III}$ and $\gamma_{Rd,II}$, and $z_b$ only to $\gamma_{Rd,III}$

| case | | $p_{f,0} = 10^{-7}$ $\{p_{f,Rd}; p_{f,bd}\} = 10^{-1}$ | | | | $p_{f,0} = 10^{-7}$ $\{p_{f,Rd}; p_{f,bd}\} = 10^{-2}$ | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $z_b$ | $z_d$ | $\gamma_{Rd,III}$ | $\gamma_{Rd,II}$ | $z_b$ | $z_d$ | $\gamma_{Rd,III}$ | $\gamma_{Rd,II}$ |
| 1 | REF | 4.42 | 1.83 | **1.70** | 1.00 | 4.89 | 1.83 | **1.89** | 1.30 |
| 2 | VG10 | 4.57 | 1.88 | **1.71** | 1.00 | 5.07 | 1.88 | **1.89** | 1.30 |
| 3 | Xdm1.15 | 4.42 | 1.83 | **1.70** | 1.00 | 4.89 | 1.83 | **1.89** | 1.30 |
| 4 | Xdm1.30 | 4.42 | 1.83 | **1.70** | 1.00 | 4.89 | 1.83 | **1.89** | 1.30 |
| 5 | α01VQ30 | 8.32 | 4.38 | **1.34** | 1.00 | 9.62 | 4.38 | **1.54** | 1.30 |
| 6 | α01VQ20 | 6.44 | 3.27 | **1.38** | 1.00 | 7.37 | 3.27 | **1.58** | 1.30 |
| 7 | α01VQ40 | 10.26 | 5.49 | **1.31** | 1.00 | 11.92 | 5.49 | **1.53** | 1.30 |
| 8 | α05VQ30 | 5.85 | 2.91 | **1.42** | 1.00 | 6.65 | 2.91 | **1.61** | 1.30 |
| 9 | α05VQ20 | 4.93 | 2.29 | **1.51** | 1.00 | 5.54 | 2.29 | **1.70** | 1.30 |
| 10 | α05VQ40 | 6.86 | 3.52 | **1.37** | 1.00 | 7.86 | 3.52 | **1.57** | 1.30 |
| 11 | α08VQ20 | 4.27 | 1.60 | **1.87** | 1.00 | 4.71 | 1.60 | **2.07** | 1.30 |
| 12 | α08VQ40 | 4.65 | 2.06 | **1.59** | 1.00 | 5.19 | 2.06 | **1.77** | 1.30 |
| 13 | VRd10VRb25 | 4.42 | 2.07 | **1.63** | 1.10 | 4.89 | 2.07 | **1.81** | 1.46 |
| 14 | VRd15VRb25 | 4.42 | 2.50 | **1.48** | 1.23 | 4.89 | 2.50 | 1.64 | **1.67** |
| 15 | VRd05VRb10 | 2.22 | 1.83 | **1.12** | 1.06 | 2.37 | 1.83 | 1.19 | **1.19** |
| 16 | VRd10VRb10 | 2.22 | 2.07 | 1.07 | **1.20** | 2.37 | 2.07 | 1.15 | **1.39** |
| 17 | VRd15VRb10 | 2.22 | 2.50 | 0.97 | **1.37** | 2.37 | 2.50 | 1.04 | **1.65** |
| 18 | VRd05VRb15 | 2.70 | 1.83 | **1.25** | 1.04 | 2.92 | 1.83 | **1.34** | 1.22 |
| 19 | VRd10VRb15 | 2.70 | 2.07 | **1.20** | 1.16 | 2.92 | 2.07 | 1.29 | **1.40** |
| 20 | VRd15VRb15 | 2.70 | 2.50 | 1.08 | **1.31** | 2.92 | 2.50 | 1.17 | **1.63** |
| 21 | VRd05VRb20 | 3.42 | 1.83 | **1.44** | 1.02 | 3.74 | 1.83 | **1.58** | 1.26 |
| 22 | VRd10VRb20 | 3.42 | 2.07 | **1.38** | 1.13 | 3.74 | 2.07 | **1.51** | 1.43 |
| 23 | VRd15VRb20 | 3.42 | 2.50 | 1.25 | **1.27** | 3.74 | 2.50 | 1.37 | **1.64** |
| 24 | VRd05VRb25 | 4.42 | 1.83 | **1.70** | 1.00 | 4.89 | 1.83 | **1.89** | 1.30 |
| 25 | VRd10VRb25 | 4.42 | 2.07 | **1.63** | 1.10 | 4.89 | 2.07 | **1.81** | 1.46 |
| 26 | VRd15VRb25 | 4.42 | 2.50 | **1.48** | 1.23 | 4.89 | 2.50 | 1.64 | **1.67** |
| 27 | VRd05VRb30 | 5.74 | 1.83 | **2.02** | 0.98 | 6.47 | 1.83 | **2.28** | 1.34 |
| 28 | VRd10VRb30 | 5.74 | 2.07 | **1.94** | 1.08 | 6.47 | 2.07 | **2.19** | 1.50 |
| 29 | VRd15VRb30 | 5.74 | 2.50 | **1.76** | 1.20 | 6.47 | 2.50 | **1.98** | 1.70 |
| 30 | VRd05VRb35 | 7.49 | 1.83 | **2.41** | 0.96 | 8.58 | 1.83 | **2.76** | 1.38 |
| 31 | VRd10VRb35 | 7.49 | 2.07 | **2.31** | 1.06 | 8.58 | 2.07 | **2.64** | 1.54 |
| 32 | VRd15VRb35 | 7.49 | 2.50 | **2.09** | 1.18 | 8.58 | 2.50 | **2.40** | 1.73 |
| 33 | VQ20α08VRd10VRb25 | 4.27 | 1.88 | **1.74** | 1.10 | 4.71 | 1.88 | **1.92** | 1.46 |
| 34 | VQ40α08VRd10VRb25 | 4.65 | 2.30 | **1.55** | 1.10 | 5.19 | 2.30 | **1.73** | 1.46 |
| 35 | VQ20α08VRd15VRb25 | 4.27 | 2.34 | **1.52** | 1.23 | 4.71 | 2.34 | **1.68** | 1.67 |
| 36 | VQ40α08VRd15VRb25 | 4.65 | 2.71 | **1.44** | 1.23 | 5.19 | 2.71 | 1.60 | **1.67** |
| 37 | VQ20α01VRd10VRb25 | 6.44 | 3.54 | **1.39** | 1.10 | 7.37 | 3.54 | **1.59** | 1.46 |
| 38 | VQ40α01VRd10VRb25 | 10.26 | 5.88 | **1.34** | 1.10 | 11.92 | 5.88 | **1.55** | 1.46 |
| 39 | VQ20α01VRd15VRb25 | 6.44 | 4.00 | **1.35** | 1.23 | 7.37 | 4.00 | 1.54 | **1.67** |
| 40 | VQ40α01VRd15VRb25 | 10.26 | 6.52 | **1.31** | 1.23 | 11.92 | 6.52 | 1.53 | **1.67** |
| 41 | VQ20α05VRd10VRb25 | 4.93 | 2.53 | **1.49** | 1.10 | 5.54 | 2.53 | **1.68** | 1.46 |
| 42 | VQ40α05VRd10VRb25 | 6.86 | 3.80 | **1.38** | 1.10 | 7.86 | 3.80 | **1.58** | 1.46 |
| 43 | VQ20α05VRd15VRb25 | 4.93 | 2.94 | **1.40** | 1.23 | 5.54 | 2.94 | 1.58 | **1.67** |
| 44 | VQ40α05VRd15VRb25 | 6.86 | 4.28 | **1.34** | 1.23 | 7.86 | 4.28 | 1.54 | **1.67** |
| 45 | VQ20α08VRd05VRb15 | 2.51 | 1.60 | **1.32** | 1.04 | 2.68 | 1.60 | **1.41** | 1.22 |
| 46 | VQ40α08VRd05VRb15 | 2.96 | 2.06 | **1.21** | 1.04 | 3.23 | 2.06 | **1.32** | 1.22 |
| 47 | VQ20α08VRd05VRb35 | 7.33 | 1.60 | **2.68** | 0.96 | 8.38 | 1.60 | **3.07** | 1.38 |
| 48 | VQ40α08VRd05VRb35 | 7.73 | 2.06 | **2.20** | 0.96 | 8.89 | 2.06 | **2.53** | 1.38 |
| 49 | VQ20α01VRd05VRb15 | 4.50 | 3.27 | **1.16** | 1.04 | 5.02 | 3.27 | **1.29** | 1.22 |
| 50 | VQ40α01VRd05VRb15 | 7.47 | 5.49 | **1.14** | 1.04 | 8.45 | 5.49 | **1.30** | 1.22 |
| 51 | VQ20α01VRd05VRb35 | 9.88 | 3.27 | **1.77** | 0.96 | 11.62 | 3.27 | **2.08** | 1.38 |
| 52 | VQ40α01VRd05VRb35 | 15.06 | 5.49 | **1.61** | 0.96 | 18.02 | 5.49 | **1.92** | 1.38 |
| 53 | VQ20α08VRd15VRb15 | 2.51 | 2.34 | 1.07 | **1.31** | 2.68 | 2.34 | 1.14 | **1.63** |
| 54 | VQ40α08VRd15VRb15 | 2.96 | 2.71 | 1.09 | **1.31** | 3.23 | 2.71 | 1.19 | **1.63** |
| 55 | VQ20α08VRd15VRb35 | 7.33 | 2.34 | **2.18** | 1.18 | 8.38 | 2.34 | **2.49** | 1.73 |
| 56 | VQ40α08VRd15VRb35 | 7.73 | 2.71 | **1.99** | 1.18 | 8.89 | 2.71 | **2.29** | 1.73 |
| 57 | VQ20α01VRd15VRb15 | 4.50 | 4.00 | 1.13 | **1.31** | 5.02 | 4.00 | 1.25 | **1.63** |
| 58 | VQ40α01VRd15VRb15 | 7.47 | 6.52 | 1.15 | **1.31** | 8.45 | 6.52 | 1.30 | **1.63** |
| 59 | VQ20α01VRd15VRb35 | 9.88 | 4.00 | **1.72** | 1.18 | 11.62 | 4.00 | **2.02** | 1.73 |
| 60 | VQ40α01VRd15VRb35 | 15.06 | 6.52 | **1.61** | 1.18 | 18.02 | 6.52 | **1.93** | 1.73 |

## Data availability

Data will be made available on request.

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