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Original Research Article

Development of Deflection Capacity Enhancement Factor

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ABSTRACT

The deflection requirement check plays a key role in the reinforced concrete (RC) slab design. Computing serviceability failure probability of RC structural unit poses many difficulties, and available literature finding according to Eurocode standard reveals inconsistency in safety level values especially with the use of different load configurations. However, such information is lacking with respect to the safety performance under the simplified span-depth (alternate) consideration for deflection check. Hence, the need for probabilistic framework for the alternate deflection requirement check is necessary. Therefore, this paper presents the drawback mitigation through the development of deflection performance enhancement that employs a rational scheme while maintaining an acceptable closed form solution. This study adopts a numerical design example, the result on the implemented limit state performance shows improvement upon the probabilistic limit state function for the simplified deflection check method, and this led to a development that will play a vital role in computation of deflection requirement using the simplified method.

1. INTRODUCTION

In the present contemporary world, the increasing concern for serviceability requirement cannot be overemphasized with the coming into lime light of complex structural units that are of great importance (Ellingwood *et al.*, 1986). Majority of the present-day codes serviceability methods are deterministic based approach that focuses on collapse state which negates or give little insight into the serviceability provision especially for the probability based limit state design codes (Hossain and Stewart, 2001). Although, at the Ultimate Limit Serviceability (ULS) design, the ultimate strength load combination is largely based on reliability-based code calibration, and it suffice reasonably in achieving uniform reliability in structural performance appraisal (Stewart, 1996). However, there is no clear distinction between un-serviceability state and collapse in contributing to economic loss in the events of failure even though there are suggestions that shows the former failure mode largely contributes (Hossain and Stewart, 2001).

In serviceability analysis considering deflection, failure occurs if the allowable deflection is less than the actual deflection (Stewart, 1996; Rosowsky and Fridley, 1997; Hossain and Stewart, 2001). Literature survey reliably shows that serviceability condition results in structural defects (Stewart, 1996; Daniel, 2014). The serviceability limit state deflection prediction of RC structure is associated with many uncertainties. As such, the limit state deflection in codes is still obscured and likely to be conservative (Hossain and Stewart, 2001). This led to an important issue regarding how realistic are the current code allowable deflection limits.

A serviceability problem in general applies to horizontal members, which includes displacement and vibration checks. Literature shows several studies are available that investigates the safety value consistency under different materials and forms (SAKO, 1999; Daniel, 2014). Most of these studies were necessitated because of variable uncertainties associated with strength and load parameters under serviceability limit state. Clearly, the importance of using probability-based approach in understanding to make possible amends to the code provision of allowable serviceability requirement is a matter of necessity (Hossain and Stewart, 2001). Many study findings support the use of probabilistic model for reliability analysis because it can effectively quantify the serviceability requirement rationally (Leicester, 1993; Holicky, 1998; Stewart and Rosowsky, 1998). For example, Stewart (1996) investigations demonstrated the application of probabilistic approach on slab serviceability to American and Australian design standards. However, while appraisal to European standard is still very limited (Daniel, 2014), and many other available literatures are solely on deterministic considerations. Recently, reliability assessment to Eurocode in serviceability was presented but for beams (Daniel, 2014). Serviceability condition of structural building are categorised in to three state; the deformation and the other two are state of motion and deterioration conditions, respectively (Galambos and Ellingwood, 1986). This study focuses on former condition than the latter two because of its pronounced effect on the typical slab types chosen for this study. Serviceability failure occurs if the basic allowable (code specified deterministic value) deflection value is less than the actual deflection under the influence of the designed loads. This deterministic deflection limits still plays an important role in establishing the safety bounds for the serviceability requirement using probabilistic based design (Melchers, 1999).

Structural deflections are categorised in to the static and dynamic groups (Galambos *et al.*, 1973). The detailed classification and the grouping effects on occupant can be found in Daniel (2014). In most cases, dynamic issues are treated as static using equivalent static load before the advancement of innovative technology. As it applies to all problems related to static and dynamic, with the only difference between the two being time considerations (Daniel, 2014). Galambos *et al.* (1973) presented a detailed state of the art overview on static and dynamic issues relating to the serviceability, with exception to long-term deflection (Daniel, 2014). Deflection check requirement plays a key role in the RC slab design, and concrete strength ultimately influences its deformation resistance capacity (Albrecht, 2002). Practical field engineers experience significantly contributed to the evolution of allowable deflection guide that are found in different design codes of practice, but how realistic are the codes specified 'the allowable deflection' (Hossain and Stewart, 2001)? Principally, the field observation records are extremely essential in formulating the probabilistic calculation for deformation requirement.

No doubt the determination of serviceability failure probability of RC structural unit poses lots of difficulties due to unspecified clear cut of serviceability failure probability in the code of practice (Stewart, 1996). Although some research, findings suggested a rational model for computing serviceability failure probabilities (Melchers, 1999; Hossain and Stewart, 2001). However, the quest for new realistic deflection capacity model becomes necessary because majority of the existing models tends to overestimate deformation value (Gilbert, 1988). Honfi *et al.* (2012) reliability-based serviceability limit state study resulting to Eurocode standard reveals the safety level inconsistency under different load configurations, but negating the simplified deflection check (*l/d*) method consideration. Interestingly, no literature findings are

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available on this simplified deflection check requirement to the European standard. This means that this study will comprehensively explore the probabilistic evaluation of deflection requirement based on the current simplified practice while negating incremental deflection. This study negation of the incremental deflection is due to its difficulty in real world assessment as highlighted (Hossain and Stewart, 2001).

Therefore, lack of probabilistic framework for the alternate deflection requirement check for RC slab designs to Eurocode necessitates this paper. Therefore, in balancing both safety and design economy of a building must look inwards to the issues of developing a probabilistic code for the simplified deflection check method because there is need to have an acceptable framework to improve the serviceability-limit state performance.

2. METHODOLOGY

There are two different approaches for checking the deflection requirement for RC slab design based on Eurocode-2 (EC2) provisions, and these are either through the theoretical deflection calculation or by limiting span-depth *l/d* ratio (Bond *et al.*, 2006). Therefore, for homogeneous elastic system, the limiting *l/d* ratio if the steel ratio ρ provided is less than reference steel ratio $\rho_o$value is given by Equation (1):

$$\frac{l}{d} = k\left[11 + \frac{1.5\sqrt{f_{ck}}\rho_o}{\rho} + 3.2\sqrt{f_{ck}}\left(\frac{\rho_o}{\rho} - 1\right)^{1.5}\right] \quad (1)$$

or when $\rho > \rho_o$

$$\frac{l}{d} = k\left[11 + \frac{1.5\sqrt{f_{ck}}\rho_o}{\rho - \rho'} + \frac{\sqrt{f_{ck}}}{12}\sqrt{\frac{\rho'}{\rho_o}}\right] \quad (2)$$

Compression reinforcement ρ' is zero in Equation (2) for the slab type considered in this study, and

$$\rho_o = 0.001\sqrt{f_{ck}} \quad (3)$$

Where f_{ck} is the concrete characteristic strength. For two-way slab design, it is customary to check using the shorter span l_x under the limiting span-deflection requirement for the respective Equations (1) and (2). Similarly, the parameter k is characterised by span direction and its end conditions, and its value for interior and end span conditions are 1.5 and 1.3, respectively, and for cantilever and simply support conditions are 0.4 and 1.0, respectively (Bond *et al.*, 2006). Figure 2 shows the general algorithm for the deflection requirement checks to EC2 provisions for RC slab. The parameters F_1, F_2 and F_3 are factors for flange beam, brittle finishes and reinforcement stress factors, respectively. The use of the either Equations (1) or (2) and expressing them in basic variables forms results in working with two basic variables that includes f_{ck} and h. The flexural reinforcement A_s and width $b$are deterministic quantities.

Figure 1 show typical continuous slab layout for this study. It is a rectangular slab type, having a long (l_y) - to-short (l_x) dimension ratio of 2:1. Due to arrangement symmetry, four different geometric are shown; one short edge discontinuous (OSED), two adjacent edge discontinuous (TAED), one long edge discontinuous (OLED) and interior panel (IP). Their parametric values for the different end conditions are comprehensively given in EN (1992). Hence, Figure 2 shows the study chart for the deflection capacity violation.

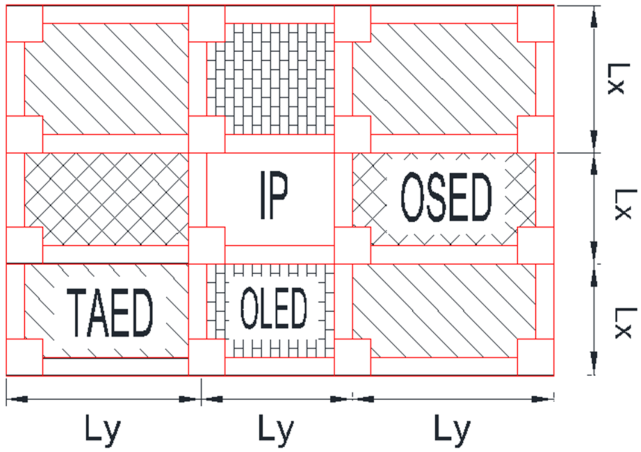

Figure 1: Typical floor layout

2.1. Limit State Function Modification

This study examines the deflection requirement based on the limiting *l/d* ratios where the traditional deflection computation is limited. Hence, in order to establish a probabilistic deflection check guide for the simplified deflection check method while maintaining an acceptable closed form solution applicable to all the limit-state violation safety datum, a variable deflection enhancement λ_{defl} factor was introduced to modify the limit state function as shown in Equation (4).

$$g(x) = \frac{l}{d} - \lambda_{defl} * actual\ {}^{l}\!/_{d} \tag{4}$$

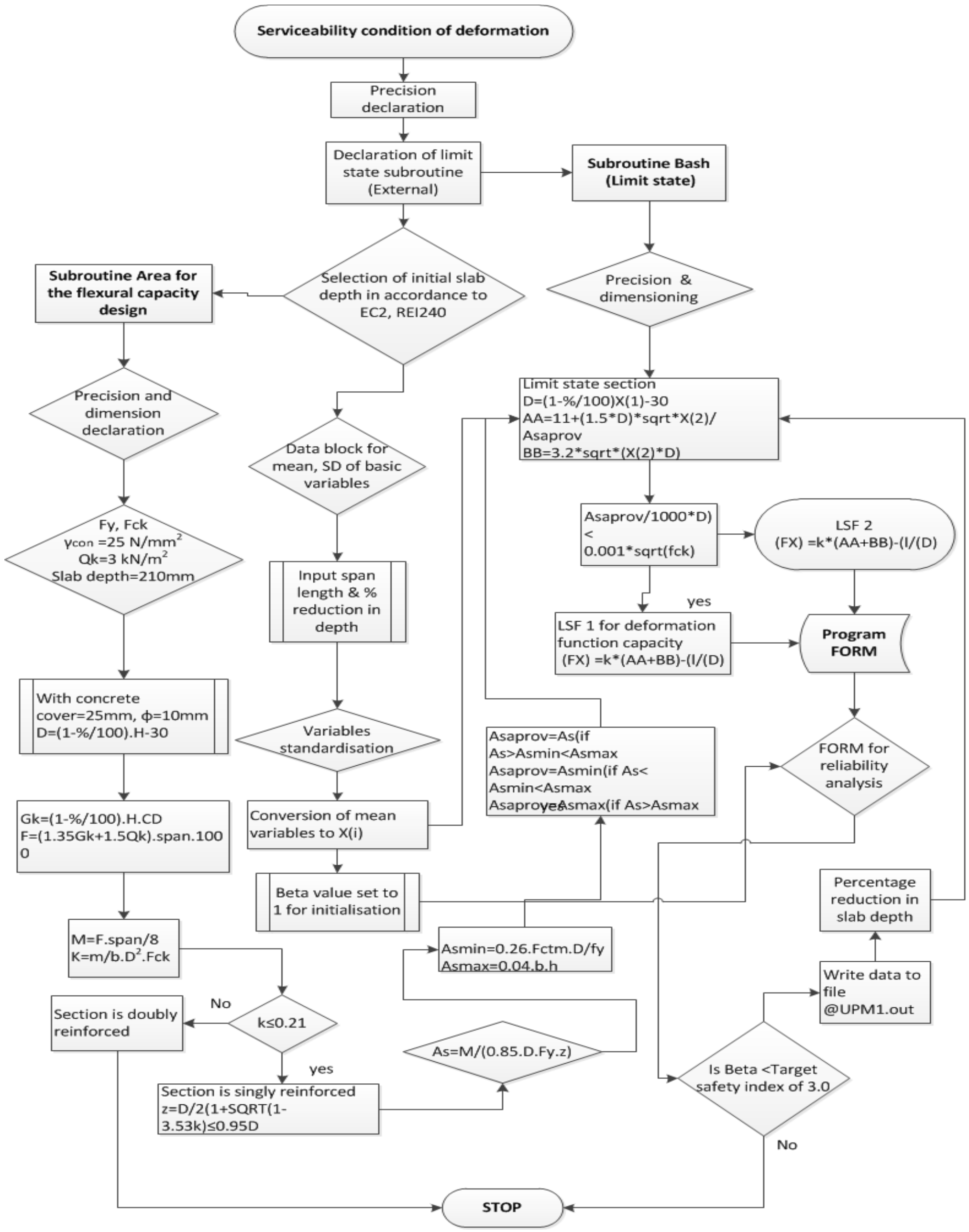

Figure 2: Deformation capacity violation

3. RESULTS AND DISCUSSION

The provision of adequate strength will not guarantee satisfactory performance of flexural member, though the accident-free requirement in the normal service life is of paramount importance (Tahsin and Md. Ruhul, 2007). Studies have shown most codes calibrations of structural members focus on ULS. However, as demonstrated in the literature, checking for SLS is vital. The reliability in serviceability conditions according to the Eurocodes is scant, and what is available in the literature is shown to be inconsistent (Daniel, 2014).

Daniel (2014) recently presented a study on the reliability of flexural members in serviceability for different materials. In those studies, the author considered the long deflection using simple creep model for deflection calculation, and the determination of the safety index using Monte Carlo simulation. However, in this study, the simplified *l/d* which aimed at controlling the deflection without rigorous calculations is adopted because it is the preferred approach in checking the serviceability of flexural member (Estee, 2010). Stewart and Rosowsky (1998) showed that the serviceability limit state violation is proportional to *l/d* and is mostly influenced by f_{ck}. On this background, this study similarly presents the safety responses using several strength classes as depicted in Figure 3.

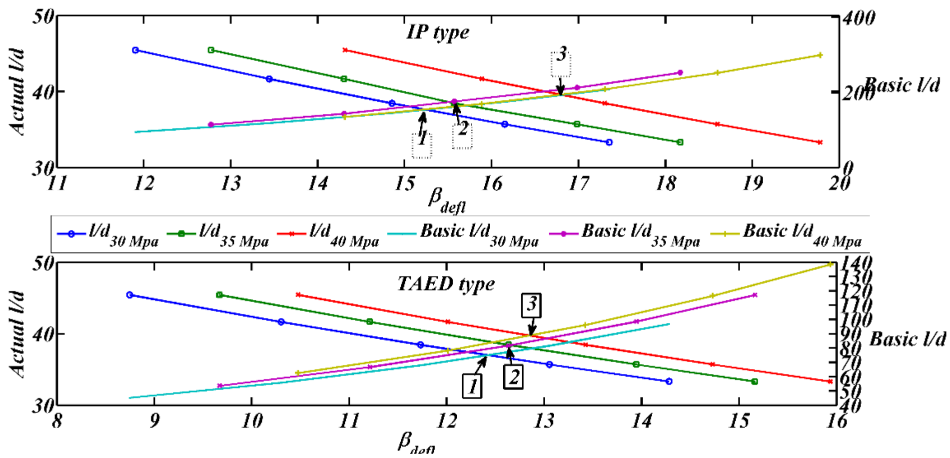

Figure 3: Serviceability limit state response for two continuous slab types

Figure 3 shows the deflection safety index β_{defl} performance, and it reveals that concrete strength class change will influence the serviceability safety performance. This behaviour supports findings in the literature that show that deflection estimates are mostly influenced by f_{ck} (Stewart and Rosowsky, 1998). The alternate deflection requirement check (*l/d*) principle as described previously, is to ensure the basic *l/d* at worst case scenario should not be less than the actual *l/d*. In terms of equilibrium, the undesirable condition is when the basic *l/d* < actual *l/d*. The three numeric points on Figure 3 show the equivalent equilibrium points with the respective f_{ck} class, just before transiting to the undesired situation. It is rational to suggest from the results, that this can serve as upper limiting datum for the probabilistic design of typical RC slabs considering the *l/d*.

An intriguing aspect of the points depicted in Figure 3 is that, because of the f_{ck} influence, the optimal maximum point occurs at different sections for the three considered strength classes. However, the slab end type influence is immaterial, because both slab *IP* and *TAED* show similar results for optimal slab depth reduction (shown as % within the range indicated in parentheses). For example, with 30 MPa: Actual *l/d* (10 - 15%), basic *l/d* (5 - 15%); 35 MPa: actual *l/d* (10%), basic *l/d* (10%), and for 40 MPa: actual *l/d* (5 - 10%), basic *l/d* (10 - 15%). In a similar parametric analysis with increasing span length, the study results presented in Table 1 shows decreasing safety performance. However, Table 1 shows the non-convergence (Nc) situation especially with increasing span and concrete strength class. The lengthier span is liable to cause excessive deformation, and this necessitated the application of a span-depth reduction factor of 0.7 for span exceeding 7 m (Estee, 2010).

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Table 1: β_{defl} characteristics influenced by change in length

Span	*IP* Type						*TAED* Type					
	30 MPa		35 MPa		40 MPa		30 MPa		35 MPa		40 MPa	
L (mm)	Basic *l/d*	β_{defl}	Basic *l/d*	β_{defl}	Basic *l/d*	β_{defl}	Basic *l/d*	β_{defl}	Basic *l/d*	β_{defl}	Basic *l/d*	β_{defl}
6000	116.18	14.07	140.61	14.96	166.27	15.74	54.73	10.82	65.38	11.76	79.76	12.58
	97.90	12.85	118.22	13.75	139.61	14.53	46.01	9.59	-	Nc	-	Nc
	81.42	11.53	97.97	12.43	115.46	13.23	-	-	-	Nc	-	Nc
	66.78	10.10	79.94	11.01	93.88	11.82	-	-	-	Nc	-	Nc
	54.55	8.85	64.18	9.47	74.96	10.28	-	-	-	Nc	-	Nc
7000	71.43	11.15	85.07	12.09	100.75	12.90	-	-	-	-	-	-
	60.61	9.92	72.29	10.86	84.71	11.68	-	-	-	-	-	-
	51.00	8.59	60.36	9.54	70.35	10.37	-	-	-	-	-	-
	-	Nc	-	Nc	-	Nc	-	-	-	-	-	-
	-	Nc	-	Nc	-	Nc	-	-	-	-	-	-

Nc: non-convergence

As expected, the β_{defl} value varies between the two slab types IP and TAED; for example, a value of 15 - 17 for IP type and a similar value of just 12 - 13 for TEAD type. These differences could be due to the applied moment magnitude. In a similar, but deterministic point of view, Estee (2010) comparatively quantified the influence of β_{defl} under the deflection requirement using different codes and standards that includes the Eurocode. The author's findings also support the previously reported finding by (Vollum and Hossain, 2002). Interestingly, the literature has shown that the EC2 design specifications led to less conservative design, but for steel reinforcement ratio ρ>1.0%. The implication of these findings is that the use of common target safety value should be discouraged. Arguably, the current codes allowable safety limit placed much emphasis on the flexural capacity, rather than the shear and deflection consideration for the simple reason that the flexural capacity defines the general slab characteristics. This means that there is the need to consider independent limiting values for shear and deflection, especially in relation to probabilistic RC slab design.

3.1. Deflection Capacity Enhancement

The reliability results show highly significant variation between the ratios considered. Hence, taking advantage of this variation and again assuming adoption of the reliability safety level of 3.6 as found in literature (Honfi *et al.*, 2012) the probabilistic deflection enhancement factor is evaluated herein.

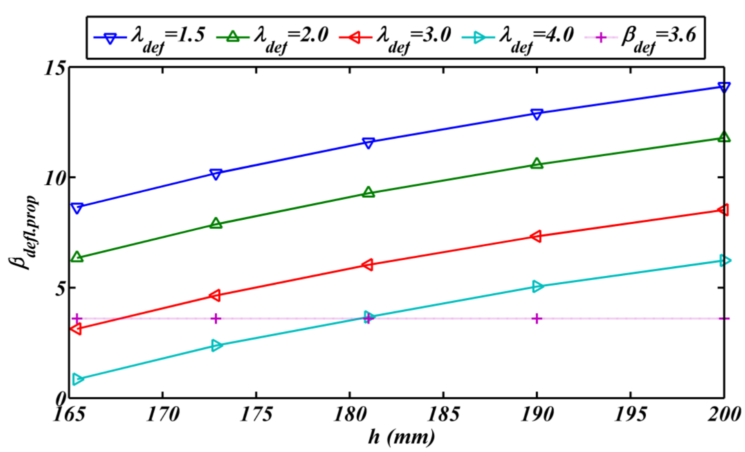

Figure 4: Deflection capacity enhancement factor

Figure 4 that depicts the resulting use of the expression in Equation (4), gives λ_{defl} value of 5.15 is obtained by linear interpolation by considering the design depth. This value is the minimum required in achieving the deflection safety target $\lambda_{deflprop}$. This literally means the actual deflection requirement check can be enhanced significantly to the bridge the gap for the typical limit state consideration adopted for the study analysis. However, the deduced value is from the use of single concrete strength class of 30 MPa.

4. CONCLUSION

This paper attempts to provide solution to a major challenge that contributes to design conservatism due to the lack of a probabilistic framework for an alternate deflection requirement check. This work addresses this challenge by implementing a rational-based approach in developing schemes for limit state enhancement. The study adopts a numerical design example, the result on the implemented limit state performance shows improvement upon the probabilistic limit state function for the simplified deflection check method. Hence, this paper proposes a λ_{defl} value of 5.15 to shore up the limiting actual deflection requirement check, but under the use of a concrete strength class of 30 MPa. This development will play a vital role in deflection computation using the simplified method.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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