STRUCTURAL SYSTEM INFLUENCE ON THE SHEAR CAPACITY OF WIDE MEMBERS WITHOUT SHEAR REINFORCEMENT

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Abstract

Most shear strength models used to estimate the shear capacity of wide reinforced concrete members without shear reinforcement do not consider the structural system or the support conditions. However, some experimental results indicate that members with predominant flexural action, such as cantilever beams, may benefit from higher bending moments at the support. These results suggest that the structural system or the support conditions can influence the shear strength. In this paper, we investigate the structural system influence on the shear strength of wide members. For this purpose, we review the available test results that varied the structural system, and we compared the accuracy and precision level of shear strength models from the literature according to the structural system of the members. In the analyses, we observed that the ratio of tested to predicted shear capacity is 5 – 10 % smaller for cantilever members than for simply supported beams. On the other hand, the ratio of tested to predicted shear capacity is 10-20% larger in continuous members than in simply supported ones. Although these results may indicate some influence of the structural system in the shear behavior, in this study, we did not identify physical reasons to validate this hypothesis. In this way, this tendency of results could be addressed to some bias in the database. However, we verified that the correlation between the shear capacities of wide members could be better correlated with the shear slenderness by taking into account that the behavior of some continuous members under uniformly distributed loads is similar to the simply supported ones with a reduced span length.

Keywords: *Mechanical models, shear strength, structural system, shear-transfer mechanisms, wide members.*

1. Introduction

In recent years, several researchers have contributed to a more comprehensive understanding of the shear strength of reinforced concrete members without shear reinforcement. Between the main advances, we can cite a better understanding of the size effect (Fernández Ruiz, Muttoni, and Sagaseta 2015) in the shear strength of thicker members, the influence of aggregate size d_g on aggregate interlock (*fib* 2012; SIA 2013) and the relation between the critical shear crack shape and the shear slenderness *M/Vd* (Cavagnis, Fernández Ruiz, and Muttoni 2018; Yang, Walraven, and Uijl 2017). Furthermore, kinematic measurements of the critical shear crack formation until failure clarified the contribution of each shear-carrying mechanism according to the crack location, shape, and kinematics (Campana et al. 2013; Cavagnis, Fernández Ruiz, and Muttoni 2018; Yang et al. 2018; Zarate Garnica 2018).

However, some authors verified that higher bending moments could improve the shear capacity of reinforced concrete members without shear reinforcement (Tung and Tue 2016b), which is contradictory with most models that take into account the section or axial strains (Bentz, Vecchio, and Collins 2006; Muttoni and Ruiz 2008; Yang, den Uijl, and Walraven 2016). This indicates that the load arrangement and the structural system could have some influence on the shear strength of reinforced concrete members not captured by the shear slenderness *M/Vd* or by the strain parameters. Based on this, we note that the structural system, load arrangement and support conditions effects should be investigated more in-depth.

In this study, we propose to discuss some aspects of the shear behavior of wide reinforced concrete (RC) members without shear reinforcement according to the structural system and load arrangement. For this purpose, we bring together a database with 170 test results of wide RC members under line loads over the width direction (loaded over the full width) failing in shear with different load arrangements and support conditions over the span direction. The database includes the following load arrangements over the span direction: (i) concentrated loads and (ii) uniformly distributed loads. The main geometric characteristic of these tests is that the tested members present a ratio of width to effective depth $b/d > 1$. In the next step, we evaluate the relation between the shear capacity of wide members according to different definitions of shear slenderness. Then, we present a comparison between experimental and predicted shear capacities according to different models of shear strength, including (i) *fib* Model Code 2010 (MC)(*fib* 2012), based on the Modified Compression Field Theory (MCFT)(Bentz, Vecchio, and Collins 2006); (ii) Swiss Code SIA 262 (SIA 2013), based on the Critical Shear Crack Theory (CSCT)(Muttoni and Ruiz 2008), (iii) Shear flexural strength mechanical model (SFSMM)(Marí et al. 2014), (iv) Compression Chord Capacity Model (CCCM)(Cladera et al. 2016), (v) Critical Shear Displacement Theory (CSDT)(Yang, den Uijl, and Walraven 2016), and (vi) the Critical Width of the Shear Band Theory (CWSB)(Tung and Tue 2016b).

2. Background to shear strength analyses of different structural systems

Figure 1 illustrates the main flow of forces of simply supported and cantilever members. Based on the similarity between the two cases, the same behavior would be expected from these members. However, a limited number of studies address this hypothesis. Furthermore, different mechanical models of shear strength differ about the location of the critical shear section. While strain-based models usually define the critical section close to the higher bending moment *M* (Bentz, Vecchio, and Collins 2006; Muttoni and Ruiz 2008; Yang, den Uijl, and Walraven 2016), models focused on the compression chord capacity (Cladera et al. 2016; Marí et al. 2014; Tung and Tue 2016a) propose that the critical section should be placed closer to the section of bending moment equal to the cracking moment. Based on these different critical sections, it is important to investigate the levels of accuracy and precision of these approaches under different structural systems.

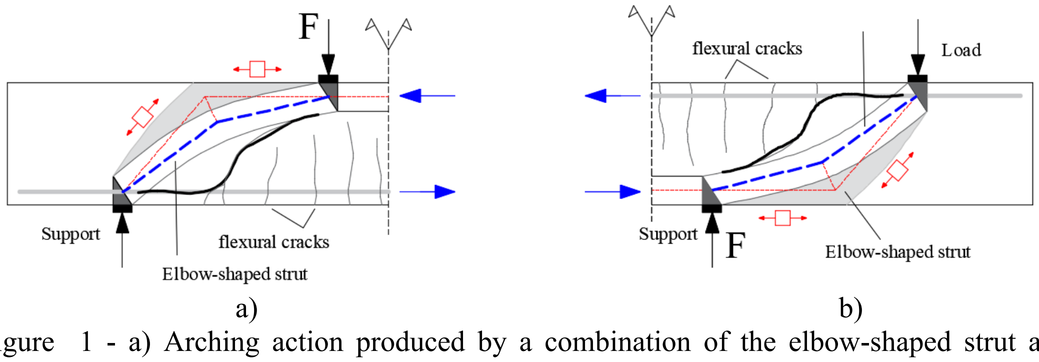

Figure 1 - a) Arching action produced by a combination of the elbow-shaped strut and direct compression strut in simply supported members and b) cantilever members.

For continuous members, Tung and Tue (2016b) verified that these members could present a more similar behavior to simply supported or cantilever members according to the bending moments over the inner support and along the span (Figure 2). In other words, if $M_{sup} > M_{span}$, the member will show similar ultimate loads and cracking patterns to cantilever ones with a cantilever length measured by the distance between the point of inflection and the inner support (Figure 2c). On the other hand, when $M_{sup} < M_{span}$, the member will behave similarly to simply supported members (Figure 2b).

Several researchers (Bentz, Vecchio, and Collins 2006; Marí et al. 2015; Muttoni and Ruiz 2008) agree that the shear behavior of reinforced concrete members without shear reinforcement is directly influenced by the shear slenderness, which can be defined in different manners. The most used definition is by the maximum ratio *M/Vd*, where *M* and *V* are the internal forces taken from the same section in the span. For simply supported members under concentrated loads in the span direction, the ratio *M/Vd* is equal to the ratio *a/d*, where "*a*" is the distance between axes of support and the position of the load, also known as the shear span, and "*d*" is the effective depth of the flexural reinforcement. For simply supported members under distributed loads in the span direction, however, the section with the maximum bending moment has zero shear force. Hence, another definition of the shear slenderness is required in this case. The most common approach calculates the same ratio *M/Vd*, but considers the maximum internal forces from different sections, resulting in $M_{max}/V_{max}d = l_{span}/4d$. Reiβen (2016) and Adam et al. (2019) proposed to define the shear slenderness based on $max\{a_1;a_2\}/d$, where a_1 and a_2 are distances from the point of inflection to M_{sup} and M_{span} in continuous members, respectively. For continuous members under concentrated loads in the shear span, the correlation between higher shear capacities with reduced values of $max\{a_1;a_2\}/d$ is clear. However, for continuous members under distributed loads, this correlation is not clear (Adam et al. 2019).

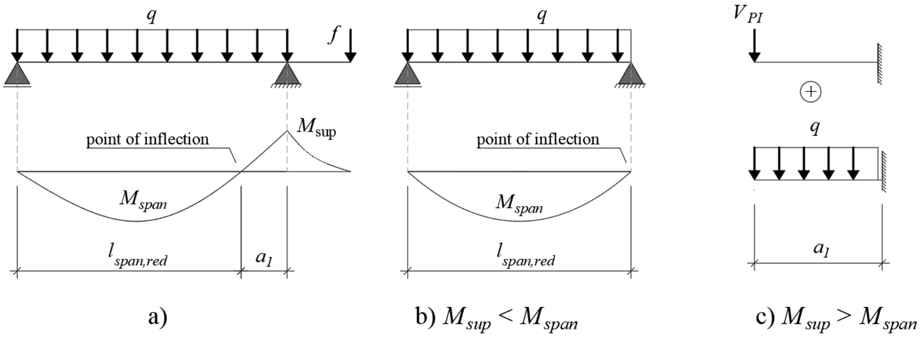

Figure 2 - a) continuous specimen under distributed load; b) equivalent simply supported member when $M_{sup} < M_{span}$ and c) equivalent problem when $M_{sup} > M_{span}$, based on the CWSB model from Tung and Tue (2016b).

In this study, we propose to take into account the observations from Tung and Tue (2016b) about the behavior of continuous members and we define the ratio $max\{a_1;a_2\}/d$ for members with $M_{sup}<M_{span}$ equal to that of simply supported members under uniformly distributed loads with a reduced span length. In this way, the following calculations for the shear slenderness parameter can be proposed (Table 1):

Table 1 – Proposed shear slenderness definition according to the static system and internal forces distribution

Structural system	Load arrangement	Bending moments	Shear slenderness λ
Simply supported	Concentrated load	-	$max\{a_1;a_2\}/d$
	Unif. Distributed load	-	$M_{max}/V_{max}.d = l_{span}/4d$
Cantilever	Concentrated load	-	$max\{a_1;a_2\}/d$
	Unif. Distributed load	-	$max\{a_1;a_2\}/d$
Continuous member	Concentrated load	-	$max\{a_1;a_2\}/d$
	Unif. Distributed load	$M_{sup} < M_{span}$	$l_{span,red}/4d$
	Unif. Distributed load	$M_{sup} > M_{span}$	$max\{a_1;a_2\}/d$

Another way to analyze the shear strength of continuous members is based on the degree of rotational restraint over the inner supports d_r. The parameter d_r is calculated by the ratio between the bending moment verified over the support in the test ($M_{sup,test}$) and the bending moment over the inner support calculated for a fixed support condition ($M_{sup,calc}$). However, previous studies indicated better correlations between shear capacities in continuous members with the shear slenderness than with the parameter d_r (Reiβen 2016).

3. Database

The database of wide members under line loads over the member width and under different load arrangements in the span direction contains 170 test results of specimens with ratio $b/d \geq 1$, the criterion we used to define experiments on wide beams and slabs. This database incorporates the tests from the following references: Adam, Herbrand and Classen (2018), Adam et al. (2019), Adam, Reiβen and Hegger (2018), Aster and Koch (1974), Bui et al. (2017), Conforti, Minelli and Plizzari (2015;2013, 2017), Furuuchi et al. (1998), Ghannoum (1998), Gurutzeaga et al. (2015), Hegger and McGrath (1980), Jäger (2002), Jäger and Marti (2005), Jäger (2007), Kani et al. (1979), Lantsoght (2013), Leonhardt and Walther (1962), Lubell (2006), Olonisakin and Alexander (1999), Rajagopalan and Ferguson (1968), Reiβen (2016) and Serna-Ros (2002). The shear capacities in the database include the self-weight in all results. Furthermore, the self-weight was taken into account to calculate the shear slenderness parameters.

The database used in this study is available in the public domain (Sousa, Lantsoght, and El Debs 2019; de Sousa, Lantsoght, and El Debs 2020) and includes 170 test results. From Sousa et al. (2019), the number of tests performed on different support conditions is noteworthy: (i) 61 on continuous members with different degrees of rotational restraint d_r, (ii) 92 on simply-supported specimens and (iii) 17 tests on cantilever members. The database also includes members with ratios a_v/d or M/Vd lower than 3, where a_v is the clear shear span or the distance between face of loading plate and face of support. Hence, this database includes members that may have failed by different shear failure modes: (i) shear compression failure and (ii) flexural shear failure (Yang, Walraven, and Uijl 2017).

4. Results

When analyzing the normalized shear capacity as a function of $max\{a_1;a_2\}/d$, see Figure 3a, we observe an increasing normalized shear capacity for a decreasing value of $max\{a_1;a_2\}/d$ for concentrated loads (CL) in the shear span. However, the shear capacity of slabs under uniformly distributed loads (DL) does not show the same increase for decreasing values of $max\{a_1;a_2\}/d$ – see blue circles in Figure 3a. In Figure 3b, we show that considering the behavior of continuous members under uniformly distributed loads with $M_{sup}<M_{span}$ similar to simply supported members with a reduced span length in the definition λ, as proposed in Table 1, tends to improve the correlation between shear capacities and shear slenderness λ to these tests.

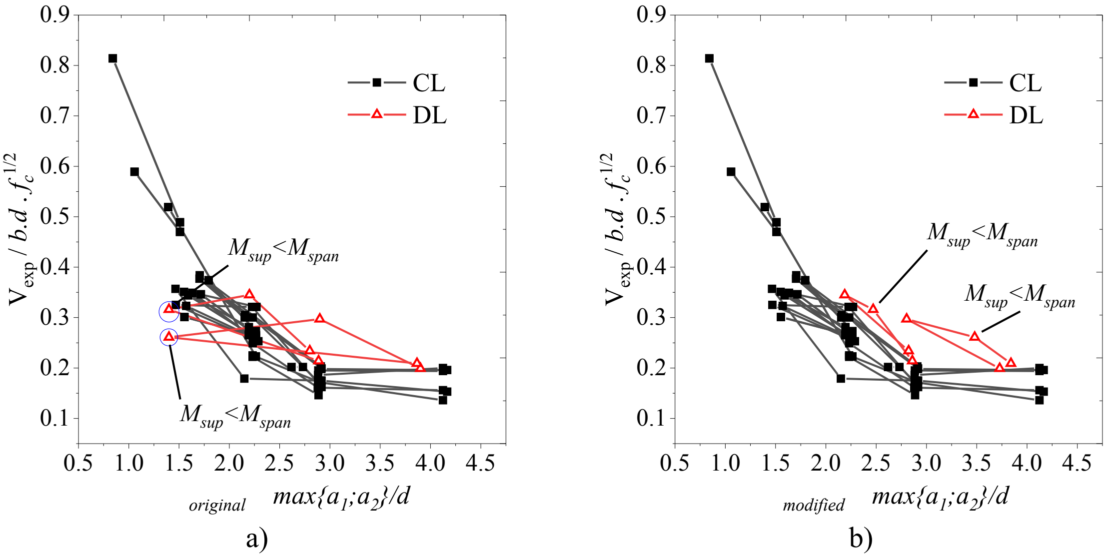

Figure 3 – Relation between experimental shear capacities and different definitions of shear slenderness λ : a) shear slenderness based on the ratio $max\{a_1;a_2\}/d$ regardless of the bending moments M_{sup} and M_{span}; b) definition of $max\{a_1;a_2\}/d$ modified to continuous members under uniformly distributed loads according to M_{sup} and M_{span}.

Most of the mechanical based-models of shear strength try to take into account the structural system by calculating the sectional forces M and V, which are well correlated to the shear strength in cases with higher shear slenderness (*M/Vd>3*). Table 2 shows a comparison between experimental and predicted shear capacities (V_{exp}/V_{calc}) for different mechanical models. The database also includes members under concentrated loads close to the support in the shear span (a_v/d < 2.5). To compare the experimental shear capacities with the calculated ones for these experiments, we reduced the applied loads (concentrated loads) to account for the benefits of direct load transfer to the support through compressive struts. In the models that did not indicate how to include this effect, we used the proposed approach by EN 1992-1-1:2005 (CEN 2005).

Table 2 shows that the ratio V_{exp}/V_{cal} in continuous members is higher than for simply supported ones for all mechanical models studied. However, we can highlight that using SIA 262 (SIA 2013) and the CSDT (Yang, den Uijl, and Walraven 2016), this difference is limited (10%). Furthermore, from Table 2, we observe that the ratio V_{exp}/V_{cal} for cantilever members is smaller than for continuous members for all models, except for the CSDT model, where this difference can be neglected. In this study, we can attribute these small differences between the prediction ratios of cantilever and simply supported members to the following aspects: (i) the small number of tests on cantilever members compared to simply supported members and (ii) self-weight influence in the results of tests on simply supported members under two-point loads, which tends to be higher than in cantilever tests, due to the reduced length of the cantilever members compared to simply supported tests.

Table 2 - Statistical evaluation of the V_{exp}/V_{cal} ratio with mechanical models according to the structural system.

Static System	N°		$\frac{V_{\exp,red}}{V_{MC}}$	$\frac{V_{\exp,red}}{V_{SIA}}$	$\frac{V_{\exp,red}}{V_{SFSMM}}$	$\frac{V_{\exp,red}}{V_{CCCM}}$	$\frac{V_{\exp,red}}{V_{CSDT}}$	$\frac{V_{\exp,red}}{V_{CWSB}}$
CT	17	AVG	1.169	1.069	0.927	1.142	1.227	1.001
		MIN	0.959	0.821	0.726	0.846	0.894	0.824
		COV	15.0%	13.8%	14.3%	13.6%	13.8%	11.2%
CS	39	AVG	1.404	1.225	1.326	1.455	1.235	1.063
		MIN	0.885	0.876	0.906	1.000	0.884	0.765
		COV	20.3%	17.6%	24.9%	22.1%	18.9%	20.2%
SS	114	AVG	1.213	1.103	1.060	1.202	1.102	1.170
		MIN	0.791	0.737	0.697	0.776	0.827	0.761
		COV	17.5%	18.4%	20.3%	19.5%	13.6%	26.3%
All	170	AVG	1.252	1.127	1.108	1.254	1.145	1.129
		MIN	0.791	0.737	0.697	0.776	0.827	0.761
		COV	19.3%	18.4%	24.4%	21.8%	16.0%	24.8%

Comparing the outcomes of the semi-empirical approaches and mechanical-based models, we observe a better accuracy and precision with the mechanical-based models (Marí et al. 2015; Tung and Tue 2016a; Yang, den Uijl, and Walraven 2016). In a joint assessment of mean value and coefficient of variation of the ratio of tested to predicted shear capacities with all models, we note that the SIA 262:2013 (SIA 2013) and CSDT models (Yang, den Uijl, and Walraven 2016; Yang, Walraven, and Uijl 2017) stand out. In this study, the same level of precision was obtained with the models based on the CSCT (SIA 2013) and the CSDT (Yang, den Uijl, and Walraven 2016; Yang, Walraven, and Uijl 2017) (COV<20%), even though our database includes members with loads close to the support (a_v/d <2.5~3) and with ratios *b/d* larger than 1, geometric features for which these models were not originally derived.

With the equations based on the SFSMM (Marí et al. 2015), CCCM (Cladera et al. 2016) and CWSB (Tung and Tue 2016a), a larger scatter between the experimental and predicted capacities was observed (COV > 20%). To explain these results, we should remember that according to the shear slenderness, the shear failure mode can change between flexural shear and compression shear. As most of these models were formulated to deal only with flexural shear failures, higher scatter could be expected in these results. At the same time, we should highlight that in the case of SFSMM (Marí et al. 2015) and CCCM (Cladera et al. 2016), the proposed formulations are easier to implement and do not require iterative procedures like the SIA code and the Model Code expressions, and presented better results than the semi-empirical equations evaluated in other studies (Cladera et al. 2016; Marí et al. 2015).

Except in the SIA 262 and CWSB models, we note a higher scatter between experimental and predicted shear capacities for continuous members than for simply supported ones, despite the larger number of tests on simply supported members (Table 2). This result may be partially related that most models did not consider that the behavior of continuous members with M_{sup} < M_{span} will be closer to simple supported ones with reduced span length, as proposed by Tung and Tue (2016b) and in Table 1. Hence, the critical section in some models can differ a lot from the real ones in continuous members.

5. Discussions

In the literature review, we identified that the structural system is commonly considered by parameters related to the shear slenderness. Initially, we expected that the structural system could have some influence not captured by the shear slenderness, mainly between simply supported and cantilever members due to the inverse effect of the self-weight in the acting shear load for these members. This effect could appear in the evaluations of the accuracy and precision of different models according to the structural systems. However, we note that these differences were limited in the database analysed (<10%) by the comparison between experimental and calculated shear capacities. This result may be linked to some bias in the databases or by the reduced thickness of the members. Based on this, we highlighted that this influence should be investigated more in-depth for members with a larger thickness (> 600 mm). Furthermore, some influences of the structural systems can occur in terms of the main shear-carrying actions at failure, which were not investigated in this study and could be assessed more properly by digital image correlations techniques.

From reviewing different theories to predict the critical shear crack section or the shear capacity of RC members without shear reinforcement, we note that most models did not indicate properly that the behavior of continuous members with M_{sup} < M_{span} would be closer to simply supported ones. Because of this, significative differences may appear in predicting the shear capacity of continuous members by not predicting the location of the critical section correctly, mainly to members under uniformly distributed loads. Most of these models may improve their results placing the critical section in these members away from the zero bending moment section in the direction of the largest bending moment.

6. Conclusions

In this study, we do not clearly identify a correlation between the structural system and the shear capacity. Minor differences in the ratio between experimental and predicted shear capacities as a function of different structural systems (Table 2) can be attributed to the database bias and limited self-weight influence. However, approaches that taking into account the structural system influence by parameters related to the shear slenderness seems to explain well the shear strength and failure mode of wide members with reduced thicknesses (< 600 mm). At this point, attention should be given to developing appropriate definitions for shear slenderness of wide members (Table 1) based on the bending moment diagram of continuous members, where the behavior can transit between simply supported and cantilever members.

At the same time, it could be observed that different models and approaches to defining the critical shear section could lead to accurate results, with the ratio V_{exp}/V_{cal} ranging from 1.108 to 1.254. This indicates that, despite being based on different criteria, most mechanical models lead to similar results by agreeing about some of the main parameters of the shear strength of wide members without transverse reinforcement, such as the shear slenderness, size effect, and the influence of the aggregates. Furthermore, we verified that the shear slenderness could be better defined assuming that continuous members under distributed loads will behave similarly to simply supported ones when the bending moment over the inner support M_{sup} reaches higher values than in the span M_{span}, as verified by other authors.

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