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STRENGTH OF ARCH-SHAPED MEMBERS IN BENDING AND SHEAR

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Abstract

Arch-shaped members are widely used for construction of tunnels, bridges, silos and shells. These members are not typically provided with transverse reinforcement and may thus have a brittle behaviour at failure. When subjected to bending or shear, traditional design methods used for straight members are not applicable due to deviation forces developing at the curved chords carrying compression and tension, which is not always accounted in design codes. In this paper, two experimental series on arch-shaped members tested by the authors are reviewed.

The first series comprises six arch-shaped members subjected to pure bending. In this case, premature spalling failures were observed due to the deviation forces of the tensile reinforcement. The observed strength to spalling is seen to be closely related to the deformation of the tensile reinforcement, indicating the interaction between bond and deviation forces. A consistent approach for their design combining these two effects is proposed and validated

The second series comprises nine specimens subjected to bending and shear. The curvature of the specimens is shown to have a positive or detrimental effect on the shear strength depending on the curvature of the member with respect to the load (convex or concave). This effect, which may turn to be significant, is proven to be consistently accounted by the physical model of the critical shear crack theory, leading to very good predictions of the strength and failure mode of the specimens.

Keywords: arch-shaped members, shear strength, deviation forces, cover spalling

1 Introduction

Reinforced concrete arch-shaped members are usually designed so as to carry mainly compression forces. However, they are usually also subjected to bending moments and shear forces. These inner forces can be due to asymmetric loading, leading to an eccentricity of the pressure line (associated to bending moments) that may not be parallel to the centroid line of the structure (associated to a shear force), see figure 1.

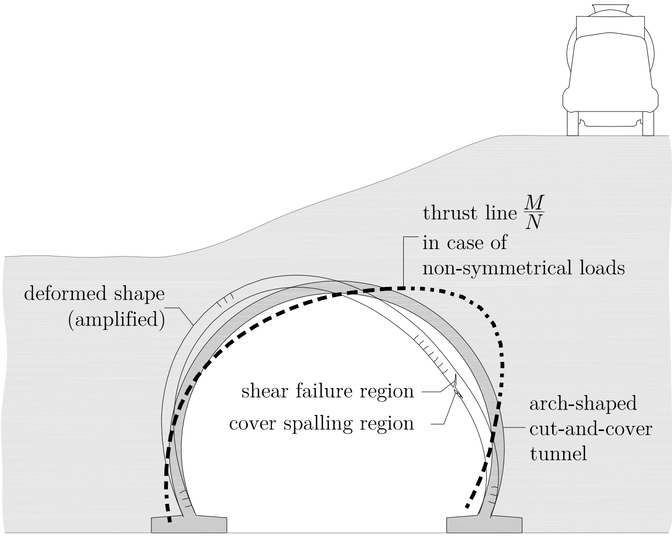

Fig. 1 Arch-shaped cut-and-cover tunnel: thrust line and deformed shape for asymmetric soil cover.

Arch-shaped members are particularly sensitive to bending moments and shear forces. Other than failures in bending (governed by yielding of the flexural reinforcement, figure 2a), brittle failures can be governing in case no transverse reinforcement is provided:

- spalling failures (figure 2b)
- shear failures (figure 2c)

Various parameters have a significant influence on the type of shear failure, namely the radius of curvature of the member R, the reinforcement ratio ρ, the level of applied bending moment M and shear force V, as well as several geometric parameters (effective depth, concrete cover, bar spacing...) and material properties (concrete compressive strength f_c, concrete tensile strength, yield strength of the reinforcement…).

Spalling failures (figure 2b) in arch-shaped members without transverse reinforcement and subjected to pure bending (V = 0) has been investigated in-depth by several authors (Fein and Zwissler, 1974; Neuner and Stöckl, 1981; Intichar et al., 2004). The interaction between shear forces and deviation forces of curved members has however not been extensively investigated (some works aiming at this problem have nevertheless been performed by Kani et al. (1979) and Intichar et al. (2004)).

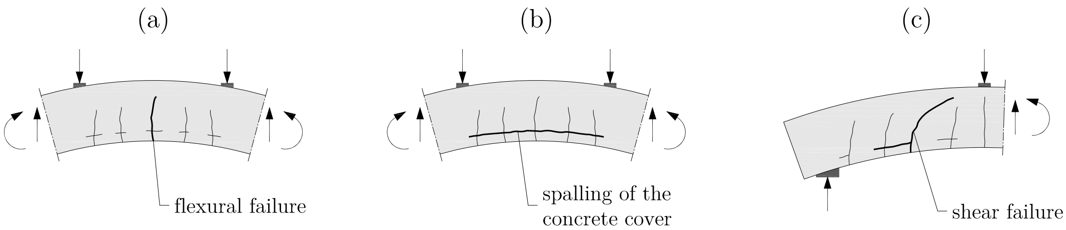

Fig. 2 Failure modes of arch-shaped members: (a) flexural failure; (b) spalling of concrete cover; and (c) shear failure.

In this paper, two experimental programmes (Fernández Ruiz et al., 2010; Campana et al., 2013) performed by the authors to investigate on the influence of the previous parameters in the various potential failure modes (bending, spalling and shear failures, see figure 2) are presented. The results will be used to discuss on the physical phenomena underlying these failures as well as to approach their analysis in a rational manner.

2 Experimental programme

2.1 Arch-shaped members subjected to pure bending (M)

The first experimental programme (Fernández Ruiz et al., 2010) is composed of six full scale tests (specimens ECP1 to ECP6, $b \times h$ = 300 × 400 mm) without transverse reinforcement. It is aimed at investigating spalling failures of the concrete cover in arch-shaped members. The six tests have the same value of the radius of curvature (R = 3700 mm) and are subjected to four-point bending (figure 3a), leading to pure bending between the central loads. Bending moments in these cases develop deviation forces in the reinforcement and may lead to premature spalling failures with a measured strength ($V_{R,test}$) lower than the theoretical bending strength ($V_{R,flex}$).

The test setup and reinforcement detailing were identical for all specimens. Only two specimens have a peculiar reinforcement arrangement with lap splices at mid-span. Also, limited variations were observed in the concrete compressive strength (f_c = 33.9 ÷ 41.7 MPa). In this test series, the main parameter investigated was the influence of the flexural reinforcement ratio ρ. Table 1 summarizes the main properties and measured results of the various tests.

2.2 Arch-shaped members subjected to simple bending (M+V)

The second test series (Campana et al., 2013) consisted of nine arch-shaped members (specimens SC7 to SC15, $b \times h$ = 300 × 400 mm) without transverse reinforcement and was designed to investigate the interaction between shear forces and deviation forces due to bending. The nine tests were subjected to three-point bending (leading to shear and bending moments in the central region) and had varying radius of curvature (figures 3b-d, table 1). Such loading combination can potentially lead to failures in shear, to failures by cover spalling or even to bending-controlled failures.

The test setup and reinforcement detailing were identical for all specimens. The concrete compressive strength was also kept as constant as possible for the various specimens (f_c = 41.2 ÷ 45.9 MPa). The main investigated parameters were the radius of curvature and the bending reinforcement ratio. Table 1 summarizes the main properties and measured results of the various tests. Figures 3b-d shows in addition that the test series was composed of specimens with positive curvature (convex shape, figure 3b), reference specimens (straight members, figure 3c) and specimens with negative radius of curvature (concave shape, figure 3d).

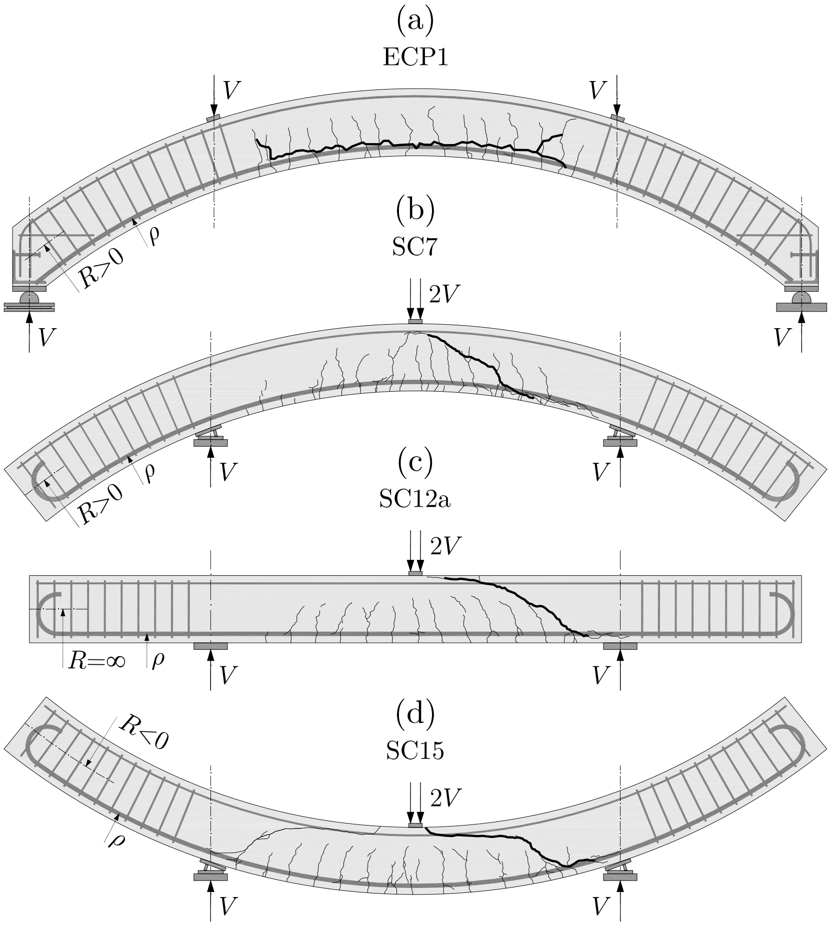

Fig. 3 Failure of representative specimens (a) spalling failure of specimen ECP1; (b) shear failure of specimen SC7; (c) shear failure of specimen SC12a; and (d) shear failure of specimen SC15.

2.3 Main results

The main results are shown in figure 4, that plots the deflection at mid-span (δ) as a function of the applied load (normalised by using $V/(b{\cdot}d{\cdot}f_c^{1/2})$). Figure 4a refers to the first experimental series (four-point bending, specimens ECP1 to ECP6). All failures developed by cover spalling in the central region subjected to pure bending (figure 3a). Failures of specimens ECP1 (ρ = 1.53%), ECP5 and ECP6 (ρ = 1.09%) were brittle (figure 4a), whereas failures of specimens ECP2 to ECP4 (ρ = 1.09% to 0.73%) develop after yielding of the flexural reinforcement with varying level of deformation capacity (figure 4a).

Table 1: Main parameters and results of the test campaign

Specimen	**Radius of curvature** R [mm]	**Flexural reinf. Ratio** ρ [%]	Test setup	**Measured strength** $V_{R,test}$ [kN]	$V_{R,test} / V_{R,flex}$ [-]
ECP1	3700	1.53	four-point bending	432	0.80
ECP2	3700	1.09	four-point bending	324	0.93**
ECP3	3700	0.90	four-point bending	287	0.96**
ECP4	3700	0.72	four-point bending	231	0.93**
ECP5	3700	1.09*	four-point bending	237	0.60
ECP6	3700	1.09*	four-point bending	197	0.50
SC7	3700	1.54	three-point bending	130	0.55
SC8	3700	1.08	three-point bending	131	0.75
SC9	3700	0.90	three-point bending	117	0.86
SC10	3700	0.73	three-point bending	117	1.00**
SC11	5350	1.54	three-point bending	120	0.51
SC12a	∞	1.49	three-point bending	149	0.62
SC13a	∞	1.06	three-point bending	137	0.77
SC14	-5350	1.53	three-point bending	154	0.65
SC15	-3700	1.54	three-point bending	167	0.71

* : specimens with lap splices (Fernández Ruiz et al., 2010)

** : yielding of the flexural reinforcement measured

Figure 4b plots the load-deflection curves for the second test series for the specimens with a constant value of the radius of curvature equal to R = 3700 mm (specimens SC7 to SC10). Figure 4c plots the same results for the specimens with constant flexural reinforcement ratio ρ = 1.53% (specimens SC7, SC11, SC12, SC14 and SC15). All failures observed in the second test series were brittle (figure 4b-c) except for specimen SC10 were failure developed after yielding of the flexural reinforcement (nevertheless the failure in the latter specimen was also due to the development of a diagonal crack as also observed by Vaz Rodrigues et al. (2010)). It can be noted that the shear failures were also associated to the development of a delamination crack parallel to the bending reinforcement.

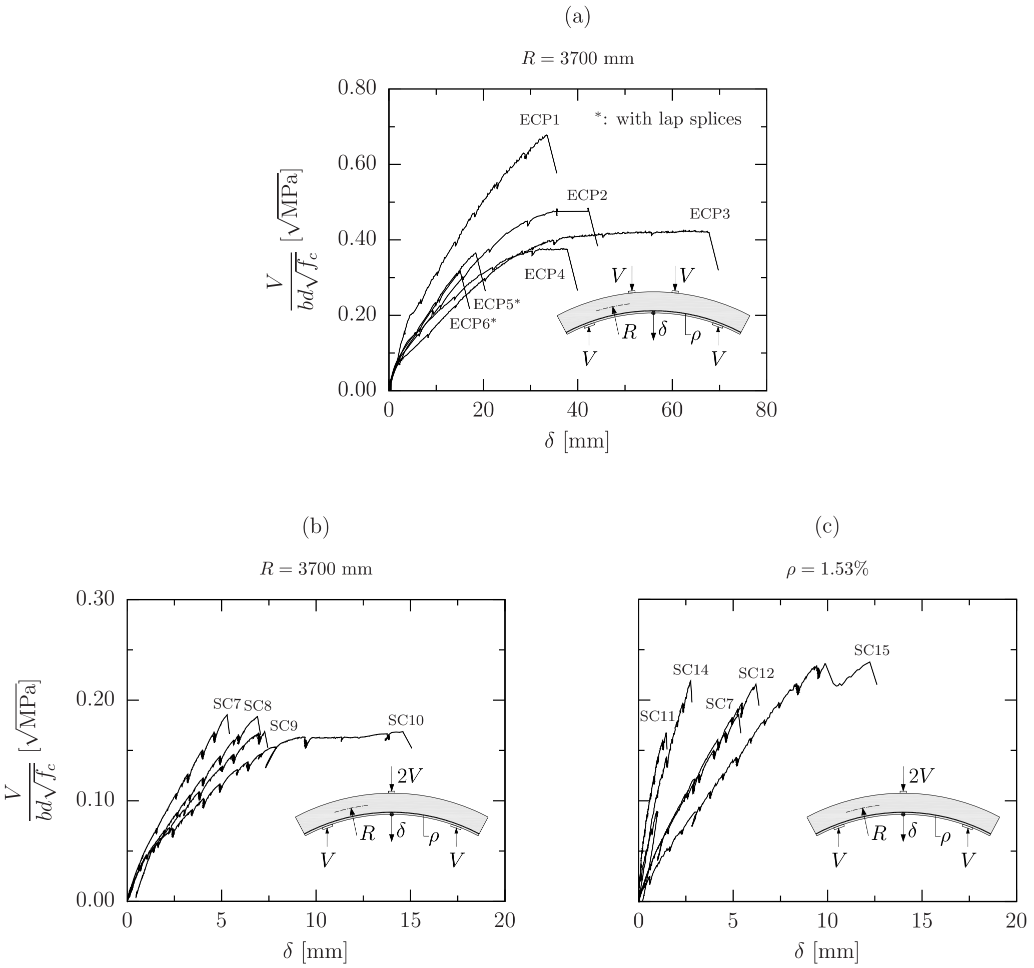

Fig. 4 Measured load-deflection curves: (a) specimens ECP1 to ECP6; and (b-c) specimens SC7 to SC15.

3 Discussion of test results

3.1 Arch-shaped members subjected to pure bending (M)

Figure 5a summarizes the results obtained for the specimens of the first test series without the specimens presenting lap splices (specimens ECP1 to ECP4). The results are shown in terms of the actual strength $V_{R,test}$ divided by the theoretical bending strength $V_{R,flex}$. This figure shows a non-negligible influence of the reinforcement ratio on the strength and behaviour of the specimens. For low values of the reinforcement ratio (ECP2 to ECP4) spalling develops after reaching the flexural strength. The deformation capacity is nevertheless still limited as it is controlled by spalling of the concrete cover (figure 4a).

Based on these results, it can be shown (Fernández Ruiz et al., 2010) that spalling of the concrete cover is not only influenced by the level of the deviation forces, but also by the strain of the flexural reinforcement (with decreasing spalling strength for increasing deformations ε of the reinforcement). The first effect (deviation forces) is shown in figure 5b, where the tensile forces of the bar are equilibrated by tensile stresses developing in the concrete (σ_{td}). The second effect is due to the development of bond stresses (τ_b) between the concrete member and the reinforcement bar, refer to figure 5c. The strain ε in the flexural reinforcement develops thus additional transversal tensile stresses (σ_{tb}), that increase for larger strains in the reinforcement bar. When the sum of both stress states reaches the tensile capacity of the concrete cover, a spalling failure develops (Fernández Ruiz et al., 2010). A rational approach to determine the transversal tensile stresses developing in the concrete based on equilibrium considerations in combination with a bond model, has been presented elsewhere (Fernández Ruiz et al., 2010) leading to excellent results in terms of the failure load and failure mode.

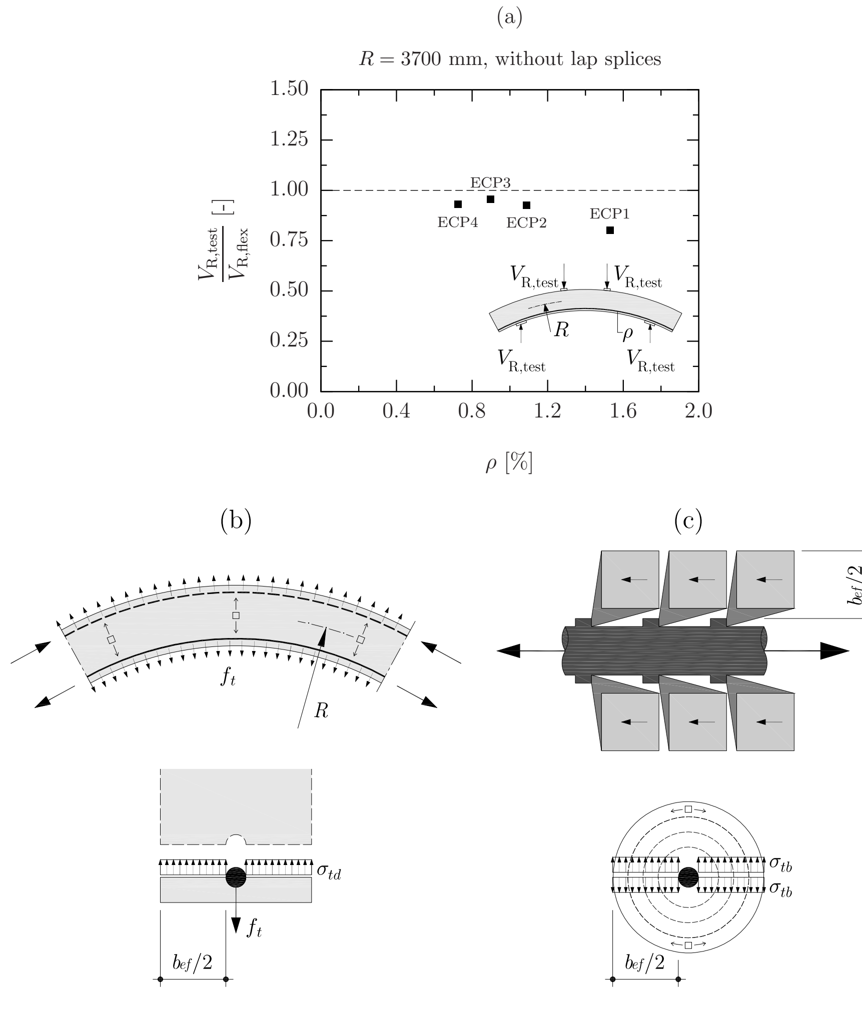

Fig. 5 Spalling failures (a) test results; (b) deviation forces of arch-shaped chords; and (c) splitting stresses due to bond.

3.2 Arch-shaped members subjected to simple bending (M+V)

Figure 6a summarizes the results of the second test series (three point bending, specimens SC7 to SC15) plotting for the specimens with a constant reinforcement ratio ρ = 1.53% the relationship between the shear strength (normalized as $V_{R,test}/(b{\cdot}d{\cdot}f_c^{1/2})$) and the ratio a/R between the shear span and radius of curvature.

This figure shows a clear influence of the radius of curvature on the strength of the elements. For negative values of the radius of curvature (concave specimens, SC14 and SC15) a larger strength is observed when compared to the reference specimen (SC12a). On the contrary, for positive values of the radius of curvature (convex shape, specimens SC7 and SC11) the strength diminishes. On the basis of these results, it can be shown (Campana et al., 2013) that the shear strength of arch-shaped members is influenced by the value of the radius of curvature. The main idea supporting this is sketched in figure 6b on the basis of a free-body analysis with an inclined crack (and positive radius of curvature). The equilibrium of forces (figure 6c) shows that a possitive curvature increases the total shear force that has to be transferred through the crack (V_c). This is justified due to the sum of the shear force V developed by the applied actions and the additional shear force ΔV due to the deviation forces. The value of ΔV can be positive or negative depending on the sign of the radius of curvature, explaining the observed test results. A rational design model based on these considerations and by using the principles of the critical shear crack theory (Muttoni and Fernández Ruiz, 2008) reveals to be very suitable for design of such members (Campana et al., 2013).

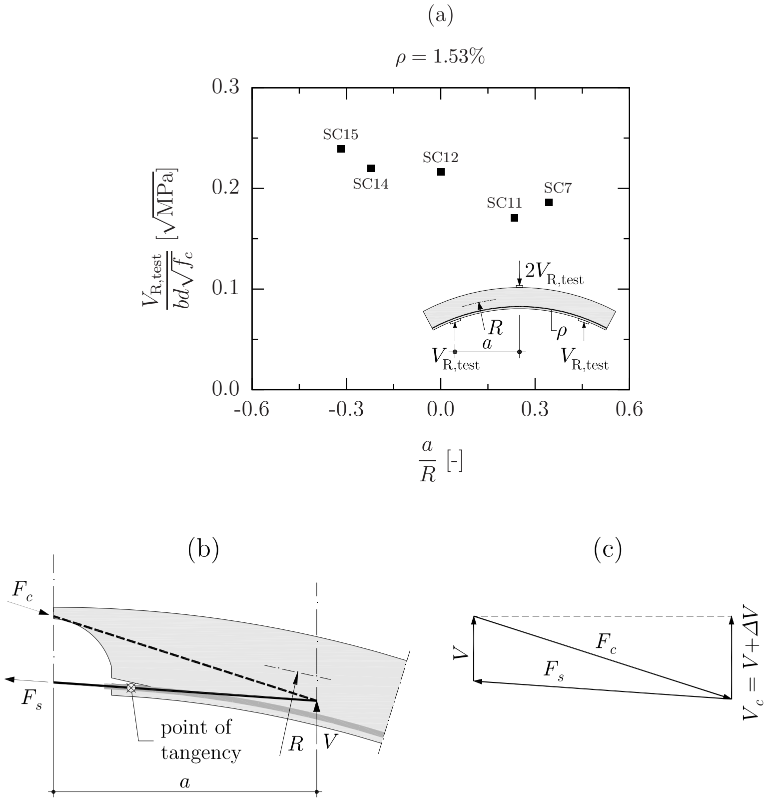

Fig. 6 Shear failures: (a) test results; (b) free-body analysis; and (c) equilibrium of acting forces at the free body.

4 Conclusions

This paper presents an experimental and theoretical investigation on the behaviour of arch-shaped members. The main conclusions of this paper are:

1) Spalling failures can be governing for the strength and deformation capacity of arch-shaped members. Such failures are due to the development of transversal tensile stresses due to deviation forces of the tension reinforcement and bond stresses. These stresses are influenced by the value of the radius of curvature and by the strains in the bending reinforcement (which depends on the reinforcement ratio for a given level of applied load). A mechanical model accounting for bond stresses and deviation forces is a consistent approach for investigating this phenomenon.
2) Deviation forces of the flexural reinforcement of arch-shaped members influence the shear strength. The shear strength can be increased or decreased depending on the sign of the radius of curvature. The observed behaviours and strengths can consistently be explained assuming that deviation forces of the flexural reinforcement are influencing the shear force that is to be carried by the critical shear crack leading to failure. A rational approach for design can be formulated by accounting for the principles of the critical shear crack theory and considering the deviation forces of the curved members

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