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Shear Resistance of Cracked Concrete Subjected to Cyclic Loading

Résistance au cisaillement de béton fissuré, soumis à un chargement répété

Die Schubtragfähigkeit von gerissenem Beton bei zyklischer Belastung

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SUMMARY

The shear resistance of cracked concrete depends upon the roughness of the crack surfaces and the dowel action of the embedded reinforcing bars. For reinforced concrete, the static crack-opening path is described using Walraven's aggregate interlock model. Results of 'high-cycle low-amplitude' tests with repeated shear loading are presented, showing that the crack behaviour can be described quasi-statically. Furthermore, 'low-cycle high-amplitude' experiments on cracked plain concrete are simulated with an extended version of Walraven's model.

RÉSUMÉ

La résistance au cisaillement d'un béton fissuré dépend de la rugosité des surfaces intérieures des fissures et de l'effet de goujon de l'armature. Pour le béton armé le cheminement de l'apparition des fissures sous un chargement statique est décrit à l'aide du modèle de Walraven sur l'interpénétration des granulats. Les résultats d'essais de nombreux cycles de faible amplitude, avec un effort tranchant répété montrent que le comportement des fissures peut être décrit comme étant quasiment statique. Des essais avec un nombre restreint de cycles de grande amplitude sont simulés avec une version développée du modèle de Walraven.

ZUSAMMENFASSUNG

Die Schubtragfähigkeit von gerissenem Beton hängt von der Rauhigkeit der Rissoberflächen und der Dübelsteifigkeit der Bewehrung ab. Für die statische Schubbeanspruchung von Rissen in bewehrtem Beton lässt sich das allmähliche Anwachsen der Rissverformungen mit dem Modell von Walraven erklären, das auf der Rauhigkeit der Rissoberflächen beruht. Versuche mit einer sehr oft wiederholten Schubbelastung zeigten, dass das Verhalten der Risse quasi-statisch beschrieben werden kann. Für Risse, die durch eine sehr hohe zyklische Belastung beansprucht werden, kann die Schädigung der Rissoberflächen mit einer zyklischen Version des Modells von Walraven berechnet werden.

1. INTRODUCTION

The problem of designing large-scale concrete structures, such as offshore platforms and nuclear containment vessels, with sufficient safety against failure is based upon the idealization of the structure as an assembly of simple structural members. The response of these members to applied loads can be investigated in experimental programs. The interactions between the elements and their redistribution of the loads can be simulated in numerical programs.
Due to tensile stresses caused by the applied loads and restrained deformations the concrete members will be cracked. Therefore, the concrete structure will respond in a highly non-linear manner to severe loading conditions such as earthquakes, wave attacks, collisions. Hence, the problem of designing complex concrete structures is shifted towards a thorough understanding of the response of the simple elements to cyclic loading conditions. The behaviour of a simple member, such as a membrane element, largely depends upon the resistance of the existing cracks to the in-plane stresses. Due to redistribution of the applied loads the crack faces are forced to slide over each other, thus transmitting shear stresses. The resistance of the cracks to shear sliding is mainly caused by the roughness due to the aggregate particles which are protruding from the crack plane. This mechanism, called aggregate interlock, is physically understood for static shear loads. Experimental and theoretical work of Walraven [1,2] provided a physical model describing static shear transfer in plain concrete. In reinforced concrete members the embedded bars crossing the cracks contribute to the transfer of shear stress due to dowel action.
This paper focusses on the behaviour of a cracked membrane element subjected to repeated and reversed in-plane shear stresses. Walraven's static model will be adapted to the case of cyclic shear loading. This study is part of the Concrete Mechanics research project sponsored by the Netherlands Centre for Civil Engineering Research, Recommendations and Codes (CUR).

2. IN-PLANE SHEAR TRANSFER

2.1 Introduction

Experiments with cyclic shear loads, including those conducted by White et al [3], Laible et al. [4], Jimenez et al [5] and Mattock [6], were tied to the behaviour of nuclear reactor vessels. Therefore, the experimental parameters were a large crack width ($\delta_n > 0.5$ mm), a small number of cycles (N = 15-100) and a high shear stress in proportion to the crack width. This type of test is called 'low-cycle high-amplitude'. The lack of information with respect to cyclic shear loading is therefore restricted to a relatively low shear stress, i.e. the 'high-cycle low-amplitude' experiments. This paper will report on this type of test, which focusses on wind and wave attack on offshore structures. As appeared from those tests, the increase in crack displacements may be as small as 10^{-6} mm/cycle, which is far less than the numerical accuracy of any mathematical model. Therefore, in this study the response of an element to 'high-cycle' fatigue is considered to be quasi-static taking into account the number of cycles to failure. In practice, a structure will be subjected to a few cycles with high amplitude shear loads after endurance of a large number of cycles with low amplitude shear loads. The response of an element to the high cyclic shear load can be calculated with an extended version of Walraven's model. However, the load history and the crack displacements due to the 'low-amplitude' cycles must be the input in the calculation.
Therefore, the analysis reported here is split into three parts. First, the static response of a crack to shear loads is described. Then, the response during the low-amplitude cycles is treated quasi-statically. Finally, Walraven's model

plain concrete is adapted to the case of cyclic loading in such a way that the load history can be neglected.

2.2 Static shear loading

For the case of static shear loading, Walraven's two-phase model describes the physical reality with a high degree of accuracy. In general, a crack runs through the matrix, but along the perimeters of the rigid aggregate particles. In the model the particles are considered as rigid spheres embedded in a rigid-plastic matrix with a yielding strength σ_{pu}. For a single particle it is shown that due to the shear sliding of the crack faces a contact area develops between the particle and the matrix material of the opposing crack plane. See Fig. 1.

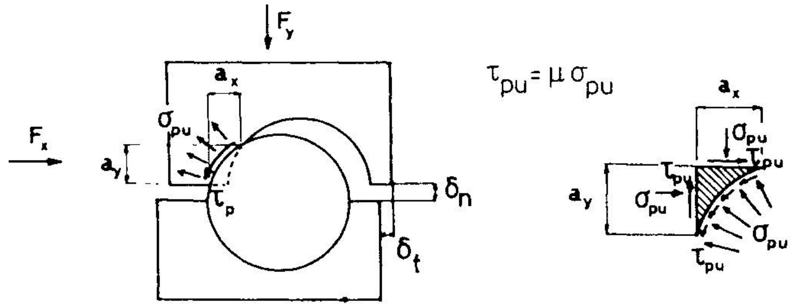

Fig. 1. Formation of the contact area for a single particle

According to Fig. 1, and taking into account all particles in the crack plane, the following constitutive equations can be formulated:

$$\tau_{ai} = \sigma_{pu}(\Sigma a_y + \mu \Sigma a_x) \tag{1}$$

$$\sigma_{ai} = \sigma_{pu}(\Sigma a_x - \mu \Sigma a_y) \tag{2}$$

The total contact areas can be analytically calculated for given crack displacements and maximum particle size. Walraven performed tests on plain concrete push-off specimens to derive expressions for σ_{pu} and μ. From the experimental results it was found that μ equals 0.4 and σ_{pu} can be calculated according to:

$$\sigma_{pu} = 6.39\, f_{ccm}^{0.56} \tag{3}$$

Apart from the test series with plain concrete push-off specimens Walraven also performed tests on reinforced specimens. Now the embedded reinforcing bars perpendicularly crossing the crack plane contribute to the shear resistance according to Rasmussen's formula [7]. It was found [8]:

$$\tau_{exp} = \tau_{ai} + \tau_d \tag{4}$$

with

$$\tau_d = \frac{5}{3} \cdot \gamma \cdot \rho \sqrt{f_{ccm}\, f_{sy}(1-\alpha^2)} \quad ; \quad \alpha = \frac{\sigma_s}{f_{sy}} \quad ; \quad \gamma = \sqrt{\frac{\delta_t}{\delta_{ni}}} \leq 1$$

Based upon the mechanism of dowel action the crack opening path for reinforced specimens is a function of the concrete strength, the steel strength and the initial crack width [8]. Experimental results of Walraven [1], Millard [9] and Mattock [6] yielded the following formulation:

$$\delta_t = \sqrt{\frac{\delta_{ni} \cdot f_{sy}}{2\, f_{ccm}}}\; (\delta_n - \delta_{ni})^{\frac{2}{3}} \tag{5}$$

Initially the crack opening path is determined by eq. (5) for increasing shear stress (See Fig. 2a.). According to eq. (4) the dowel action reaches its maximum value for δ_t equal to δ_{ni}. At the onset of a decrease in the contribution of aggregate interlock to the shear transfer the crack opening path follows the path for a constant τ_{ai} according to Walraven's model. Figure 2b-c. presents the comparison between the calculated paths and some typical crack opening paths for Walraven's and Millard's tests.

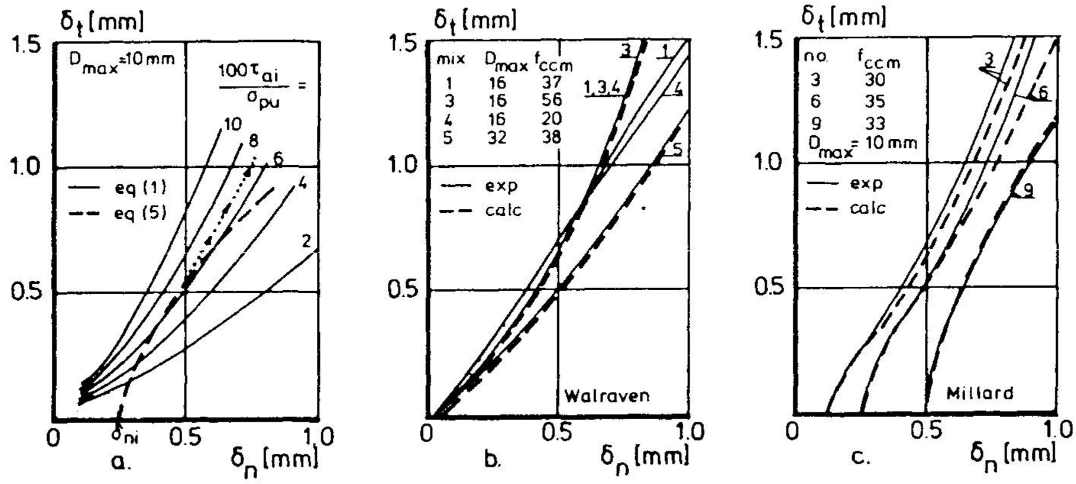

Fig. 2. Crack-opening paths according to the equations (1) and (5).

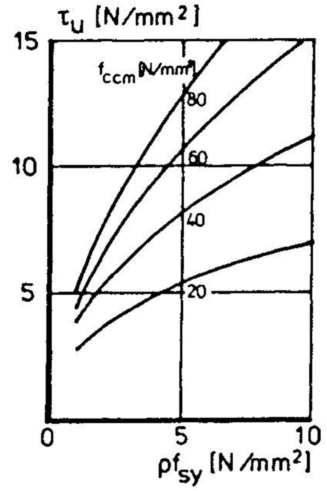

Fig. 3. The ultimate shear stress according to eq. (6) [10].

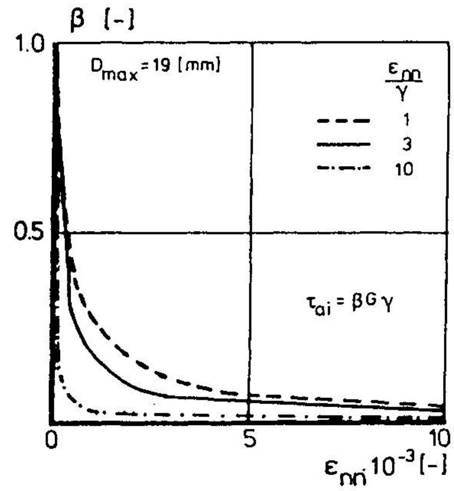

Fig. 4. Shear retention factor β according to Walraven's model [13].

The ultimate shear stress for reinforced specimens can be calculated according to eq. (6) [10]. This expression was derived empirically on basis of 88 test results [1,10,11,12]. The relation between the mechanical reinforcement ratio and the shear strength is shown in Fig. 3.

$$\tau_u = a\,(\rho f_{sy})^b \qquad (6)$$

$$\text{with } a = 0.822\, f_{ccm}^{0.406} \qquad b = 0.159\, f_{ccm}^{0.303}$$

In numerical programs of the smeared crack type a shear retention factor β is commonly used to account for the shear softening in cracks. Based upon Walraven's model an expression (eq. 7) was derived [13] (See Fig. 4). Although eq. (7) is an improvement of the relations derived by Rots [14] and Bazant et al [15] it is not possible to model the crack behaviour using one parameter β. Firstly, the interaction between strain - and shear softening must be taken into account. Secondly, the contribution of dowel action must be implemented.

$$\beta = \frac{1}{P\varepsilon_{nn}+1} \quad \text{with} \quad P = \frac{2500}{D_{max}^{0.14}\left[0.76-0.16\,\frac{\varepsilon_{nn}}{\gamma}\left\{1-\exp\left(1-6\frac{\gamma}{\varepsilon_{nn}}\right)\right\}\right]} \tag{7}$$

2.3 Cyclic shear loading; high-cycle low-amplitude

The study reported in this paper comprises 42 'high-cycle low-amplitude' tests on push-off specimens with 8 mm diameter bars perpendicularly crossing the crack plane (See Fig. 5). The variables were:

- the concrete strength f_{ccm} = 51, 70 [N/mm²] (D_{max} = 16 mm, Fuller curve)
- initial crack width δ_{ni} = 0.01-0.10 mm
- number of bars n = 4-6 (1.12-1.68 %)
- number of cycles N = 118-931731
- applied stress level: τ_m = 0.45-0.90 τ_u

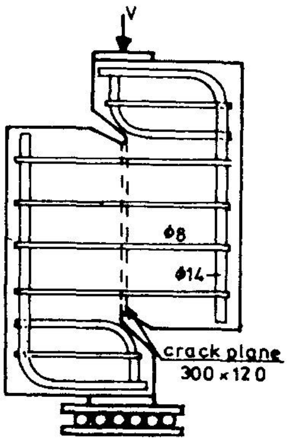

Fig. 5 Push-off specimen [12].

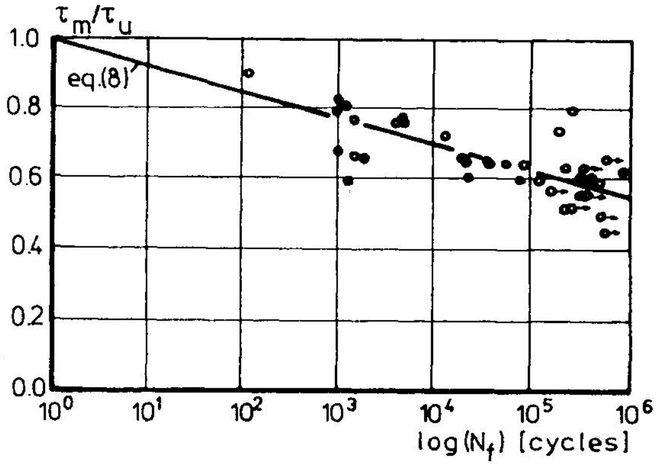

Fig. 6. The τ_m/τ_u-log(N_f)-relation [12].

All the specimens were precracked. The tests were performed load-controlled with a sinusoidal signal with 60 cycles/min. The applied stress varied between 0.3 N/mm² and τ_m (repeated loading). A complete description of the test results is given in [12]. Fig. 6 presents the relation between the applied stress level and the number of cycles to failure. This relation is approximated by the empirical relation:

$$\frac{\tau_m}{\tau_u} = 1 - 0.073 \log (N_f) \tag{8}$$

Some typical test results are presented in the Figs. 7-8. It was observed that for increasing stress-levels the increments of the crack-displacements per cycle

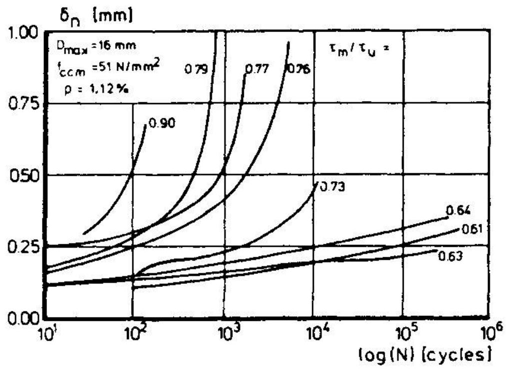

Fig. 7. The δ_n-log(N) relation for given stress-levels.

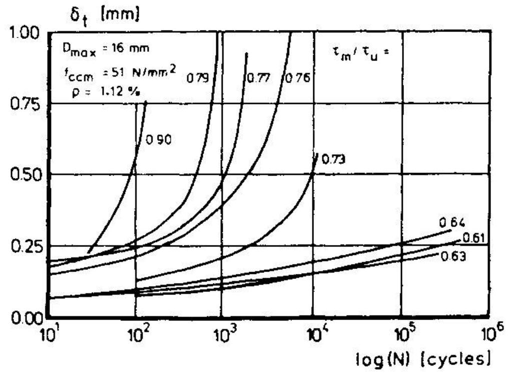

Fig. 8. The δ_t-log(N) relation for given stress-levels.

also increase. It appeared that, as for the static case, the crack opening paths were determined by a constant shear stress due to aggregate interlock. As a consequence, the contribution of dowel action also remained constant. From eq. (4) it is known that both aggregate interlock and dowel action are approximately proportional to $\sqrt[2]{f_{ccm}}$. However, no measurable decrease of the concrete strength due to fatigue was found from the test results. This was probably due to the fact that the matrix material, highly stressed in a previous cycle, detoriorated in a subsequent cycle. Therefore, unaffected matrix material was then deformed to obtain the contact areas between matrix and particles. The high loading rate with respect to the crack width could be another important factor.
Based upon the experimental observations it can be concluded that the 'high-cycle' crack behaviour can be treated statically. Provided that suitable empirical expressions describing the relations in Figs. 7-8 are available, the crack-displacements can be calculated for a given number of cycles. With eq. (1) the most favourable crack opening direction can be determined.

2.4 Cyclic shear loading; 'low-cycle high amplitude'

In this Section the model is restricted to the crack behaviour in plain concrete, so that the transfer of stresses across a crack depends upon the mechanism of aggregate interlock. For the case of a few load cycles with a relatively high applied shear stress the crack displacements per cycle are considerably larger than the numerical accuracy of a mathematical model. Hence, for this case an extended version of Walraven model can be used. In [1] Walraven already gave a qualitative description of cyclic loading tests performed by Laible [16] using his two-phase model. In [17] this idea was worked out numerically, taking into account the actual deformations caused by 100 particles. The contact area of each particle was determined using ten points situated in the contact zone (See Fig. 9). Now eqs. (1)-(2) become (j = 1-100):

$$\tau_{ai} = \sigma_{pu} \left(\Sigma a_{y,j} + \mu\, \Sigma a_{x,j}\right) \tag{9}$$

$$\sigma_{ai} = \sigma_{pu} \left(\Sigma a_{x,j} - \mu\, \Sigma a_{y,j}\right) \tag{10}$$

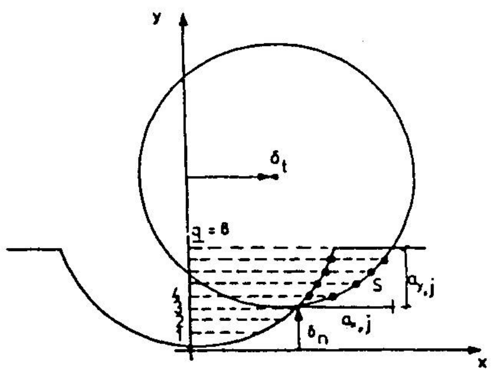

Fig. 9. Extended two-phase model of Walraven [17]

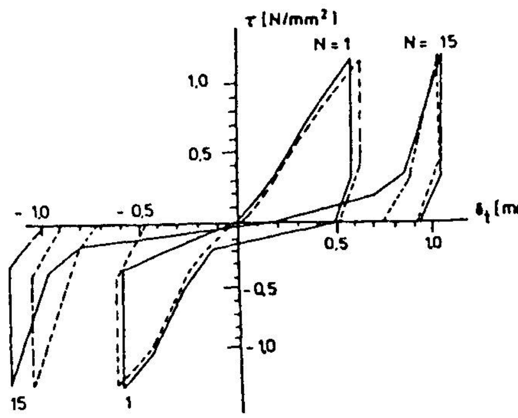

Fig. 10. Calculated and experimental result for Laible's test A1 [17]

Laible performed 'high-amplitude' tests on precracked plain concrete push-off specimens, for which the normal restraint stiffness was obtained by means of external bars. The experimental result of test A1 was predicted quite satisfactorily (See Fig. 10). To find the unknown material parameters, the model was fitted to the first static cycle: μ equal to 0.2 and the contact area reduced by 25 percent. In agreement with the experimental results of the 'low-amplitude' tests, the matrix strength was kept constant for each cycle. In the calculation

the normal restraint stiffness was prescribed according to the experimental results.
This model can be used to perform a sensitivity analysis of the shear stiffness for various parameters, such as initial crack width, normal restraint stiffness and different stress levels. However, the model is too complex for implementation in a finite element program.
A major problem inherent in the physical behaviour of the crack and in this extended model is the fact, that the load history must be taken into account. In consequence, it cannot be used with a quasi-static description of previous 'low-amplitude' cycles.
Therefore, the extended two-phase model of Walraven [17] is simplified assuming that for each particle the 'load history' goes back as far as the last increment of the crack width and the deformation caused by the last displacement increment of the previous cycle [18]. Now, the contact area can be determined analytically, using the intersection points of three circles (See Fig. 11). These circles represent:

- Circle 1: deformation before the last crack width increment
- Circle 2: particle position for the momentary displacements
- Circle 3: end deformation of the previous load cycle.

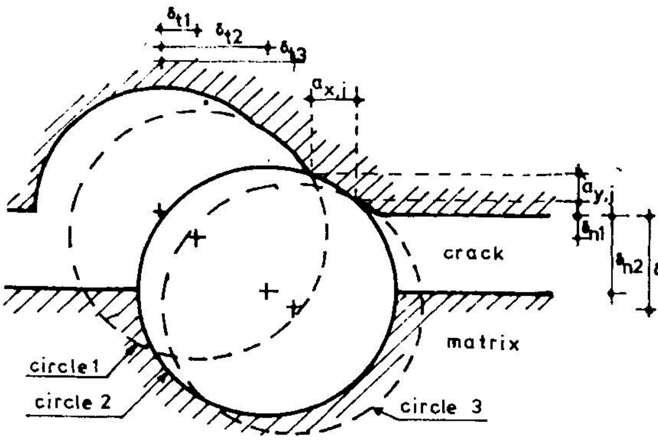

Fig. 11. Simplified calculation of contact zone

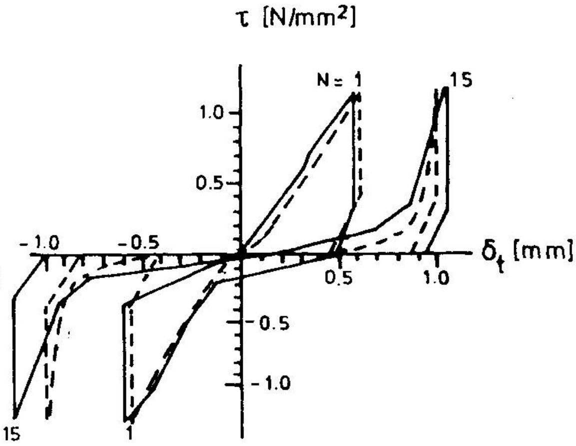

Fig. 12. Predicted result for test A1 neglecting most of the load history

Fig. 12 presents the calculated response for Laible's test A1 using the simplified model. It appeared that the experimental result can be simulated neglecting most of the load history. Therefore, the simplified model can be used in combination with preceding 'low-amplitude' cycles.

2.4 Concluding remarks

- Shear transfer in cracked reinforced concrete is based upon the mechanism of aggregate interlock and dowel action.
- Crack behaviour can be treated quasi-statically for the case of repeated 'high-cycle low-amplitude' shear loading.
- The extended model of Walraven can be used to simulate 'high-amplitude' tests.
- For implementation in numerical programs the number of particles must be reduced to a maximum of three.
- Apart from implementation of the extended aggregate interlock model the cyclic response of the mechanism of dowel action must be described in order to predict the shear resistance of reinforced cracks subjected to cyclic shear loading.

3. NOTATION

D_{max} = maximum particle diameter [mm]
N = number of cycles
a,b,P,α,γ = empirical parameters
f_{ccm} = cube crushing strength [N/mm²]
f_{sy} = steel yield strength [N/mm²]
a_x, a_y = projected contact areas [mm²]
δ_n, δ_t = crack width, shear slip [mm]
ε_{nn}, γ = normal, shear deformation
τ, σ = shear, normal stress [N/mm²]
β = shear retention factor
μ = coefficient of friction
ρ = reinforcement ratio

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