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Development of a Stop Criterion for Load Tests based on the Critical Shear Displacement Theory

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A mis padres Franklin y Carmen y a mi hermana Ana Paula, por haberme acompañado en cada paso y siempre estar ahí. Sin ustedes todo esto no es posible.

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RESUMEN

La capacidad de carga de los puentes que se encuentran en operación es un aspecto importante para la seguridad de los usuarios. Los ensayos de carga de prueba (Proof load tests) son una opción útil para evaluar si un puente cumple con los requisitos de los códigos actuales para su operación. Para llevar a cabo este ensayo, una carga que representa el total de las cargas vivas mayoradas es aplicada sobre el puente de manera controlada. Con el fin de evitar daños permanentes en estas estructuras se emplean criterios de parada (Stop Criteria), sin embargo estos criterios generalmente son aplicables para ensayos realizados en flexión. Por esta razón, en el presente trabajo de investigación se busca también analizar la capacidad en cortante de los puentes ensayados mediante cargas de prueba. Para lo cual se empleara la Teoría del Desplazamiento Crítico de Cortante (Critical Shear Displacement Theory) con el fin de desarrollar un nuevo criterio de parada basado en la contribución de cada uno de los mecanismos de resistencia a cortante presentado en la Teoría del Desplazamiento Crítico de Cortante. Por último este nuevo criterio de parada será evaluado con experimentos realizados en laboratorio a vigas que cumplen las condiciones necesarias para verificar el desempeño del nuevo criterio. Como resultado, se obtendrá un nuevo criterio de parada para ensayos de carga de prueba en puentes para evaluaciones de cortante, el cual además tendrá una sólida base y fundamentación teórica.

Palabras clave: Ensayos de Carga de Prueba, Cortante, Hormigón armado, Puentes, Teoría del Desplazamiento Crítico de Cortante.

ABSTRACT

The capacity of existing bridges is an important aspect regarding the safety of the traveling public. Proof load testing can be a useful option to evaluate if an existing bridge satisfies the requirements from the code. For this purpose, a load representative of the total factored live load is applied to the bridge. In order to avoid permanent damage to the structure stop criteria are needed. The stop criteria provided by the guidelines are generally based on flexure. Therefore, in this paper, a new approach is followed, taking into account the shear capacity. When developing a stop criterion for shear for proof load tests on existing bridges, there are many different approaches that could be taken. In this paper, a stop criterion is developed based on the Critical Shear Displacement Theory. A theoretical approach is followed. This approach is based on the analysis of the contribution of each of the mechanisms of shear transfer as described by the Critical Shear Displacement Theory to the shear capacity of a beam without shear reinforcement. The equations outlined by the theory are at the basis of the presented evaluation. The contribution of the compressive zone in shear to the total shear capacity of a beam is taken as the start for the development of the stop criterion. Finally, the criterion is verified with experiments on beams in the laboratory. The consequence of this development is that now a stop criterion for shear with a theoretical basis is provided.

Key words: Proof loading, Shear, Reinforced concrete bridges, Critical Shear Displacement Theory, Stop Criterion

Development of a Stop Criterion for Load Tests based on the Critical Shear Displacement Theory

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ABSTRACT: The capacity of existing bridges is an important aspect regarding the safety of the traveling public. Proof load testing can be a useful option to evaluate if an existing bridge satisfies the requirements from the code. The stop criteria provided by the guidelines are generally suitable for flexure only. Therefore, in this paper, shear is considered. When developing a stop criterion for shear for proof load tests on existing bridges, many different approaches could be taken. Here, a stop criterion is developed based on the Critical Shear Displacement Theory. The development of the stop criterion is based on the analysis of the contribution of each of the mechanisms of shear transfer. The criterion is verified with experiments on beams in the laboratory. The consequence of this development is that now a stop criterion for shear with a theoretical basis is provided.

1 INTRODUCTION

1.1 *Existing bridges*

The evaluation of the capacity of reinforced concrete slab bridges is an important aspect in terms of safety for the travelling public (Lantsoght et al. 2013). Some bridges that were built decades ago usually are not designed for the actual traffic loads, meaning that a way to check these bridges integrity and performance in actual conditions is required.

The presence of deterioration mechanisms will also affect the performance of the bridge during its lifespan, as expressed in the Model Code. The extent of deterioration should be determined upon inspection using models from data previously obtained, or by other tests and inspections that will help the professional asses the actual condition of the bridge (Chajes et al. 2000).

The approach for evaluation and assessment of these bridges is generally based on different Levels of Assessment (Lantsoght et al. 2016e) proposed in the Model Code (fib 2012). This approach allows the evaluation to be done in steps, each one leading to a higher level of accuracy, but being more time consuming as well.

The first three levels of approximation for the evaluation of existing reinforced concrete slab bridges for shear include the use of spreadsheet programmed calculations (Vergoossen et al. 2013), linear finite element models (Lantsoght et al. 2017b) and probabilistic analysis (Braml et al. 2013). If the analysis requires more accuracy, level IV should be used, which includes methods such as proof loading (Lantsoght et al. 2016e).

1.2 *Shear Assessment of Bridges*

The shear assessment of existing reinforced concrete slab bridges in the Netherlands showed that a large number of these bridges do not fulfill the code requirements for shear (Lantsoght et al. 2013). In particular, flexural shear is the failure mode that needs to be studied in further detail. Preliminary calculations indicate that the shear capacity of these bridges can be insufficient (Walraven, 2010) even though no signs of distress are observed (Lantsoght et al. 2016d). For slab bridges, proof load testing can be a valid way to demonstrate that a bridge fulfils the code requirements.

2 REVIEW OF LITERATURE

2.1 *Proof loading*

For evaluating the capacity of bridges in general two types of load tests have been used:

1. diagnostic load tests, which evaluate the stiffness and performance of a bridge (Fu et al. 1997, Russo et al. 2000, Olaszek et al. 2014),
2. proof load tests, in which the bridge is subjected to higher load levels in order to evaluate its capacity (Saraf et al. 1996, Anay et al. 2016, Lantsoght et al. 2016b, Halicka et al. in press).

Proof load tests use a load level corresponding to the factored live loads and are used for a direct evaluation of the structure (Lantsoght et al. 2017a). The main objective is to provide enough data in order to establish safe service live loads for bridges in operation (NCHRP 1998), which will be useful in order to assess if the bridge should be kept in service, or should be repaired, posted, or replaced.

One of the crucial aspects of proof loading is the way of determining if the bridge passes the evaluation or not. Stop criteria have been developed that allow the professional to monitor the structural response during the proof load test. If a stop criterion is exceeded, the test should be terminated and further loading is not permitted (Lantsoght 2017). In principle, stop criteria are defined as the onset of irreversible damage.

The American Concrete Institute (ACI) committee 437 provides the code requirements for Load Testing of Existing Concrete Structures (ACI Committee 437 2013) and is applied for evaluation of building through proof loading. The minimum requirements for test loads are established in order to determine the structural safety and serviceability of existing concrete structures. The code provides the requirements for test load magnitudes as well as different loading protocols, and finally outlines acceptance criteria based on measurements taken during the load test.

Other codes and guidelines that discuss load tests are the Manual for Bridge Evaluation (AASHTO 2016), based on the Manual for Bridge Rating through Load Testing (NCHRP 1998) as well as German guideline (Deutscher Ausschuss für Stahlbeton 2000), and British guideline (The Institution of Civil Engineers - National Steering Committee for the Load Testing of Bridges 1998). None of the mentioned guidelines allow shear-critical structures to be tested by proof loading, nnor propose any stop criterion for shear-critical structures (Lantsoght et al. 2017d). Therefore, this paper will present a newly developed stop criterion for proof load tests in shear, based on the principles of the Critical Shear Displacement Theory (Yang et al. 2016).

2.2 *Acceptance and stop criteria for proof loading*

A stop criterion is a way to evaluate if distress is produced in a bridge during a proof load test. If a stop criterion is exceeded, the test should be stopped and no further loading is permitted (Lantsoght 2017). An acceptance criterion is used after a proof load test, to see if the structure performs as required. In this case the obtained value from the test that is applied to the criterion has to be smaller than an acceptable limit for the performance.

The German Guideline proposes stop criteria for flexure, suitable for plain and reinforced concrete (Lantsoght et al. 2017a). The guideline defines the following stop criteria:

- Limiting concrete strain
- Limiting strain in the steel

- Stop criteria based on crack width
- Maximum residual deflection

For limiting concrete strain as a stop criterion, the German Guideline uses the following equation.

$$\varepsilon_{\lim} = \varepsilon_c - \varepsilon_{c0} \tag{1}$$

with ε_c = the strain measured in the proof load test, ε_{c0} = the strain caused by the permanent loads acting on the structure before placing the proof load, and ε_{lim} = the limit value for the concrete strain: 0.6%, and for concrete classes > B25 this value could be increased up to a maximum of 0.8%.

3 CRITICAL SHEAR DISPLACEMENT THEORY

The Critical Shear Displacement Theory (Yang 2014, Yang et al. 2016 , Yang et al. 2017a) uses the critical displacement at which a flexural shear crack opens as the lower bound for the shear capacity of a reinforced concrete beam without shear reinforcement. Experimental observations suggest that reinforced concrete beams without shear reinforcement fail in two different manners based on the crack pattern shown during the loading of the beam (Yang et al. 2017). These two failure mechanisms take as a basis the development of a critical inclined crack. The theory is based on one of those, the so-called “Flexural shear failure”. This shear failure mechanism occurs in beams with a large shear span.

Since the mechanics of reinforced concrete elements in shear (ASCE-ACI Committee 445 on Shear and Torsion 1998) still aren’t fully understood, various models have been proposed. The Critical Shear Displacement Theory proposes a model based the following three shear carrying mechanisms:

- Direct Shear Transfer is the force transferred in the concrete in compression. It is calculated assuming a linear stress distribution (Mörsch 1908).
- Dowel Action is the force that is transferred in the longitudinal reinforcement by the formation of a dowel crack. The theory employs the expression proposed by Baumann and Rüsch (Baumann and Rusch 1970).
- Aggregate Interlock is the force resulting from the interlocking mechanism of aggregate bridging the crack. The Critical Shear DisplacementTtheory uses the fundamental analysis of aggregate interlock (Walraven 1981).

The shear capacity according to the Critical Shear Displacement Theory is the sum of the contributions of the three previously described mechanisms of shear transfer. The contribution of Direct Shear Transfer uses the following equation:

$$V_c = \frac{d - s_{cr}}{d + 0.5 s_{cr}} V \tag{2}$$

with V_c = the shear force transferred in the compression zone, V = the total shear capacity, d = the effective depth of the element, s_{cr} = the height of the major flexural crack, expressed with the following equation:

$$s_{cr} = [1 + \rho_s n_e - \sqrt{2\rho_s n_e + (\rho_s n_e)^2}]d \tag{3}$$

in which ρ_s = the longitudinal reinforcement ratio, and n_e = the ratio between elastic moduli of steel and concrete.

The contribution by Dowel Action is calculated as:

$$V_d = 1.64 b_w Ø^3 \sqrt{f_c{}'} \tag{4}$$

with V_d = the shear force transferred by dowel action, b_w = the width of the structural member, Ø = rebar diameter, and f'_c = the concrete compressive strength.

For aggregate interlock, the following simplified expression is used:

$$V_{ai} = (f_c{}')^{0.56} s_{cr} b_w \frac{0.03}{w_b - 0.01}\left(978\Delta^2 + 85\Delta - 0.27\right) \tag{5}$$

with V_{ai} = the shear force transferred by aggregate interlock, s_{cr} as calculated with Eq. (3), w_b = the flexural crack width at the bottom of the crack:

$$w_b = \frac{M}{z A_s E_s} l_{cr,m} \tag{6}$$

in which M = the cross-sectional bending moment, z = the internal level arm, A_s = the reinforcement area, E_s = the elastic modulus of steel, and $l_{cr,m}$ = the spacing between two flexural cracks:

$$l_{cr,m} = \frac{s_{cr}}{k_c} \tag{7}$$

With s_{cr} as given in Eq. (3), and k_c = the slope of the stress line, for which a value of 1.28 can be assumed (Yang 2014). Δ represents the shear displacement in a crack. At failure, Δ reaches the critical value, to so-called critical shear displacement:

$$\Delta = \frac{d}{29{,}800} + 0.005 \leq 0.025mm \tag{8}$$

The contributions of the different shear transfer mechanism are summed to find the ultimate shear capacity of a member without shear reinforcement as shown in Figure 1.

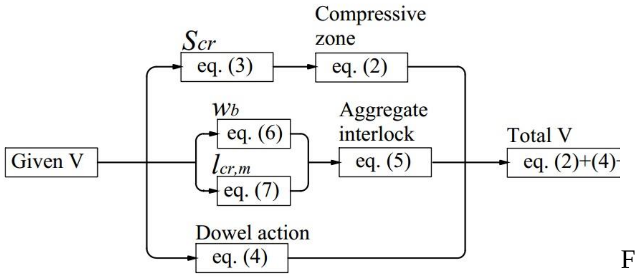

Figure 1 Flow chart for calculating the ultimate shear capacity of a reinforced concrete beam using the Critical Shear Displacement Theory (Yang et al. 2017).

4 THEORETICAL DERIVATION OF A STRAIN-BASED STOP CRITERION FOR SHEAR

For the application of the Critical Shear Displacement Theory to a practical stop criterion for field measurements, the analysis of the theory should be converted to a measurable response. For this purpose, strains are used for the stop criterion. The aim of this derivation is to develop a limiting strain for which a proof load test should be terminated. This criterion can then be used for proof load tests for shear on reinforced concrete slab bridges. Since slab bridges could be conservatively assumed as wide beams without shear reinforcement, the Critical Shear Displacement Theory can be used to predict the ultimate shear capacity and maximum load for a specimen without shear reinforcement, as well as the associated strain.

In a bridge, the self-weight of the structure, as well as the superimposed dead load and live loads lead to stresses in the cross-sections. For the development of the stop criterion, the bridge structure is simplified as a simply supported beam subjected to a single point load, which represents the proof load tandem. Figure 2 shows the beam used for the development of the stop criterion.

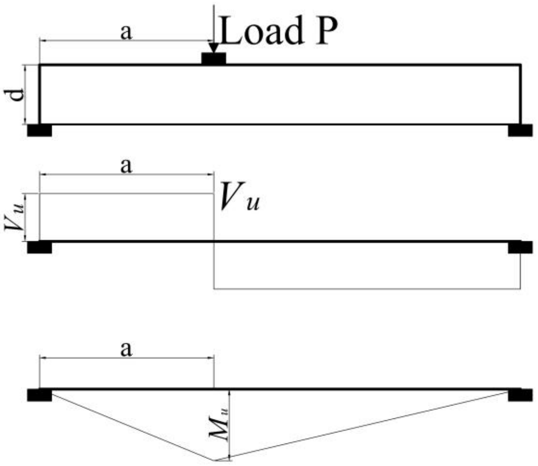

Figure 2 Simplification of slab bridge to simply supported beam, and resulting shear and bending moment diagrams.

Once the shear capacity according to the Critical Shear Displacement is obtained, the corresponding moment produced in the cross-section is determined. This bending moment, M_{CSDT}, is then used to find the associated curvature φ_{CSDT}. The value of φ_{CSDT} is found by using linear interpolation between the points of cracking of the concrete and yielding of the steel, see Figure 3. To determine the bending moment and curvature at yielding, the concrete stress block is determined by using the parabolic stress-strain relation proposed by Thorenfeldt (MacGregor and Wight 2005). It is assumed that for a shear-critical beam, M_{CSDT} lies between $M_{cracking}$ and $M_{yielding}$, the bending moments at the point of cracking and yielding, respectively. For a flexural shear failure, flexural cracking must be present. If a proper shear failure occurs, the beam will fail in shear before the steel yields. An example of the calculation procedure is available elsewhere (Benitez 2017).

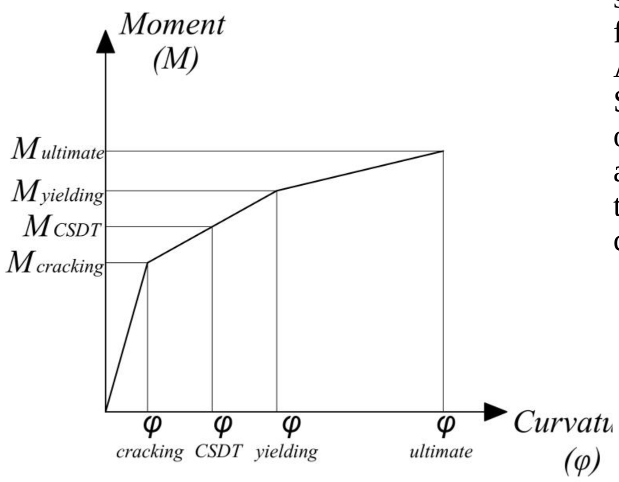

Figure 3 Theoretical moment-curvature diagram for reinforced concrete beam, showing the theoretical failure point of a shear-critical beam.

Once the curvature at the point of shear failure, φ_{CSDT} is known, a sectional analysis can be used to convert this curvature into the strain at the bottom of the cross-section. The considered cross-section and resulting strains and stresses are sketched in Figure 4. For the sectional analysis, a parabolic stress block is assumed for the concrete. The analysis is based on the horizontal equilibrium between tension and compression. When a parabolic stress block is used, an iterative procedure (see Figure 5) can be followed to find the strain at the bottom of the cross-section. This strain $\varepsilon_{c,bot}$ can then be used as the limiting strain for a stop criterion, i.e. the strain of which exceedance will result in a shear crack and possible shear failure. The resulting stop criterion $\varepsilon_{lim,CSDT}$ is then:

$$\varepsilon_{\mathrm{lim},CSDT} = \varepsilon_{c,bot} - \varepsilon_{c0} \quad (9)$$

with ε_{c0} the strain caused by the permanent loads.

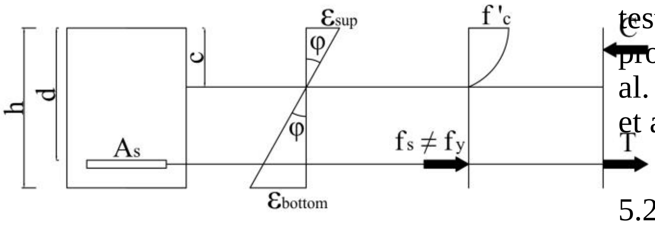

Figure 4 Sectional analysis, showing considered cross-section, resulting strains, stresses, and forces.

The proposed stop criterion, see Eq. (9), based on a limiting strain, is similar to the stop criterion for limiting concrete strain from the German Guideline (Deutscher Ausschuss für Stahlbeton 2000), see Eq. (1). Since permanent loads are present at the time of the proof load test, the maximum allowable strain during the test should be taken as the limiting strain minus the strain caused by the permanent loads.

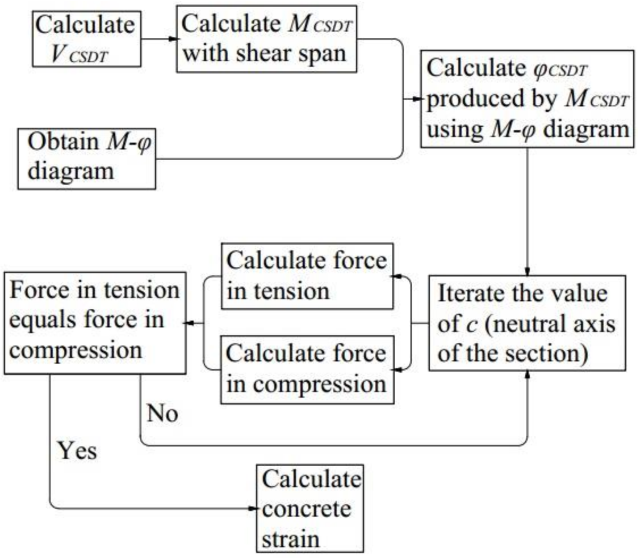

Figure 5 Flow chart for calculating limiting strain for stop criterion.

5 EXPERIMENTS

5.1 *Introduction*

For evaluating the proposed stop criterion, experimental data are used. The results of two beams, RSB03A (Lantsoght et al. 2016b) and P804B (Lantsoght et al. 2016a) are analyzed. The first beam was sawn from the Ruytenschildt Bridge (Yang 2015, Lantsoght et al. 2016c, Lantsoght et al. 2017c), and the second beam was cast in the laboratory, and tested to study the stop criteria and loading protocols for proof load testing (Lantsoght et al. 2016a, Lantsoght et al. 2017a, Lantsoght et al. 2017e).

5.2 *Geometry and material properties*

RSB03A had a total length of 6 m. The asphalt layer that was present on the bridge was only removed on this beam at the point where the load was placed, in order to maintain its flexural stiffness. P804B had a total length of 10 m and a span length of 8 m. In Table 1 the geometrical and material properties of the beams are presented.

Table 1 Geometrical and material properties of beams RSB03A and P804B

Beam	RSB03A	P804B
d (mm)	515	755
b_w (mm)	1058	300
a (mm)	1300	2500
Rebar	7ϕ22mm + 8ϕ19mm	6ϕ20mm
ρ_l	0.92%	0.83%
fc' (MPa)	52	64
fy' (MPa)	283	297

5.3 *Test procedures*

Both P804B and RSB03A are simply supported beams subjected to a single concentrated load. A cyclic loading protocol was used for beam RSB03A (Lantsoght et al. 2016b), see Figure 6. For beam P804B, the load was increased step-wise monotonically, see Figure 7.

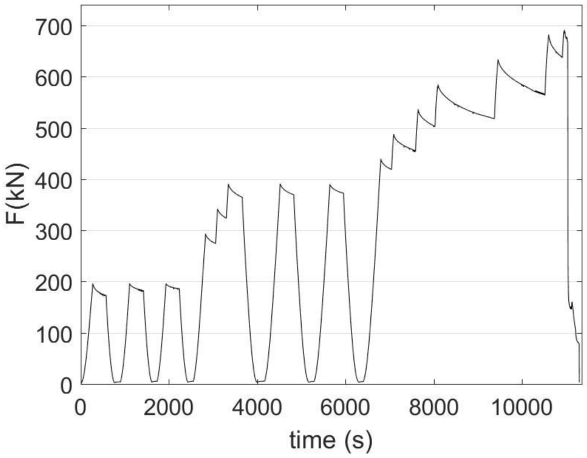

Figure 6 Loading scheme for RSB03A

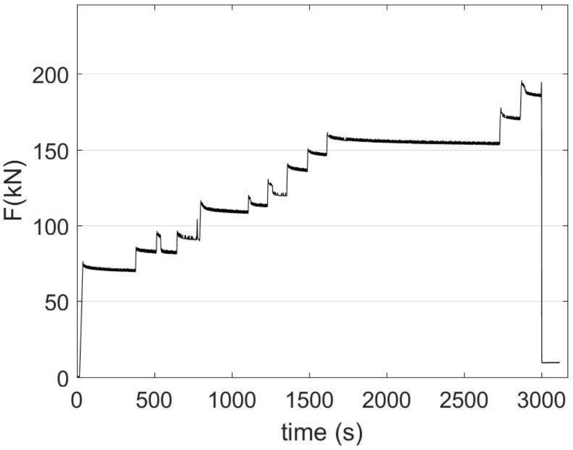

Figure 7 Loading scheme for P804B.

5.4 *Results from experiments*

Beam RSB03A failed after the formation of an inclined crack along the shear span (Lantsoght et al. 2016b). Beam P804B failed in shear after an inclined crack appeared on its shear span. Table 2 shows the test results in terms of the failure mode, ultimate shear in the test V_u, ultimate shear predicted by the Critical Shear Displacement Theory $V_{s,CSDT}$, maximum load in the test P_u, maximum load predicted by the Critical Shear Displacement Theory $P_{s,CSDT}$, and the ratio of tested to predicted load P_u/P_{CSDT}. As the cross-section of RSB03A corresponded to a strip from a full-sized slab strip, larger failure loads were found for this experiment.

Table 2 Test results of beams RSB03A and P804B

Experiment	RSB03A	P804B
Failure mode	Flexural shear	Flexural shear
V_u (kN)	546.2	178.2
$V_{s,CSDT}$ (kN)	562.5	189.3
P_u (kN)	706.7	196
$P_{s,CSDT}$ (kN)	729.1	208.3
$P_u/P_{s,CSDT}$	0.97	0.97

6 COMPARISON BETWEEN PROPOSED STOP CRITERION AND EXPERIMENTAL RESULTS

The comparison between the test results and results predicted with the Critical Shear Displacement Theory in Table 2 show an excellent correspondence between the experiment and model.

For calculating the limiting strain from the proposed stop criterion, the value of the ultimate shear from Critical Shear Displacement Theory $V_{s,CSDT}$ was used as well as the evaluation procedure outlined in Section 3. Table 3 shows the calculated limiting strains and the strains measured during the tests. For both experiments, the strains produced by the permanent loads were determined and subtracted from the limiting strains. For RSB03A the permanent load is calculated taking into account the self – weight of the beam and the weight of the asphalt layer. For beam P804B, the self-weight is taken into account as no asphalt layer was present. Table 3 shows the limiting strain from the stop criterion $\varepsilon_{lim,CSDT}$, the limiting strain according to the German guideline ε_{lim} (see Eq. 1), the maximum strain measured in the experiment ε_{exp} and the ratio $\varepsilon_{lim,CSDT}/\varepsilon_{exp}$. The load at which the proposed stop criterion is exceeded, $P_{lim,prop}$, as well as the load at which the stop criterion from the German guideline is exceeded $P_{lim,German}$ and the ratios of these loads to the maximum experimental load P_u are also presented in Table 3.

Table 3 Results of RSB03A and P804B with respect to limiting strain and load at which this strain is exceeded.

Experiment	RSB03A	P804B
$\varepsilon_{lim,CSDT}$ ($\mu\varepsilon$)	757	863
ε_{lim} ($\mu\varepsilon$)	783	767
ε_{exp} ($\mu\varepsilon$)	900	1400
$\varepsilon_{lim,CSDT}/\varepsilon_{exp}$	80%	63%
$P_{lim,prop}$ (kN)	565.0	118.7
$P_{lim,German}$ (kN)	585	111
$P_{lim,prop}/P_u$	0.80	0.61
$P_{lim,German}/P_u$	0.83	0.56

In Figure 8 and Figure 9 the measured strain versus applied load is plotted for both experiments, and the limiting strain from the proposed stop criterion is indicated on the graphs.

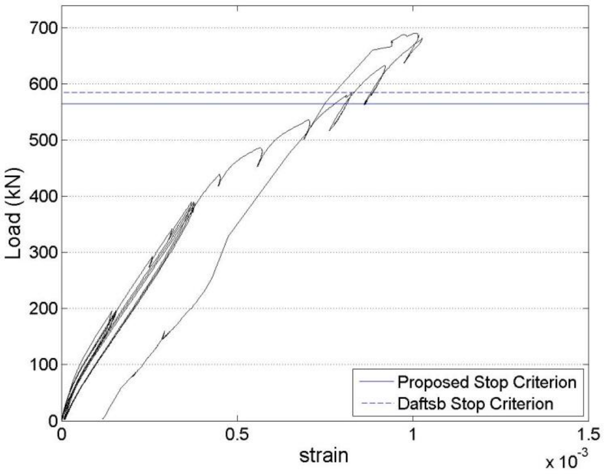

Figure 8 Load strain graph for RSB03A showing proposed stop criterion

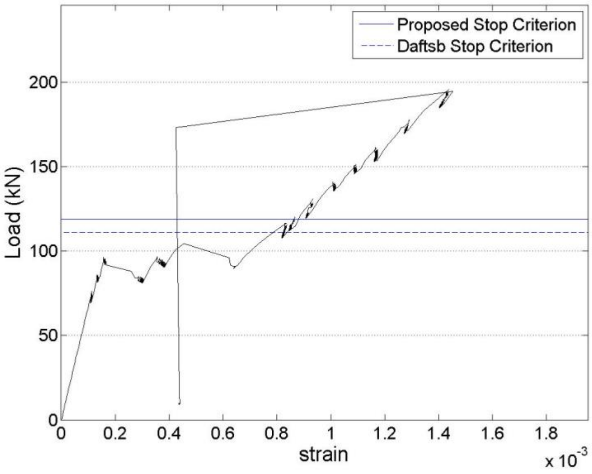

Figure 9 Load strain graph for P804B showing proposed stop criterion

The limiting strain according to the German guideline ε_{lim} is larger than the proposed strain $\varepsilon_{lim,CSDT}$ for RSB03A and smaller for P804B. This shows that a single value for the limiting strain as proposed by the German guideline is not sufficient for proof load testing for shear.

The proposed stop criterion is exceeded between 60% and 80% of the maximum load. As such, the proposed stop criterion seems to have a sufficient margin for safety for the application to proof load testing of reinforced concrete slab bridges. Further experiments, in particular on reinforced concrete slabs subjected to cycles of loads, are necessary to confirm the validity of the proposed stop criterion.

7 DISCUSSION OF PROPOSED STOP CRITERION

The proposed strain-based stop criterion has a theoretical basis, and is a significant improvement as compared to a stop criterion that uses an arbitrary limiting strain. For each tested shear-critical section, an appropriate limit for the strain can now be determined.

Strain was selected as the structural response to be monitored during proof load tests, because this response can easily be measured in the field using LVDTs, strain gages, or by using non-contact techniques such as photogrammetry (De Wilder et al. 2016, Mejia and Lantsoght 2016). The strain is monitored at the bottom of the cross-section so the measurement equipment could easily be applied, and removal of the concrete cover is unnecessary. The measurements should be taken at the same point were the target strain of the stop criterion is calculated. It is recommended to monitor the position of the center of the proof load tandem.

As a preparation for the proof load test, some preliminary calculations are required in order to assess the capacity and expected responses of the bridge that will be tested (Lantsoght et al. 2017d). The moment curvature diagram is one of these preliminary calculations. It should be calculated assuming a beam behavior with a width of 1 meter. These calculations can easily be extended to determine the limiting strain from the proposed stop criterion.

The effects of load redistribution in slabs (Lantsoght et al. 2015) and its contribution to the capacity of a bridge have not been taken into account in this stop criterion, as these are not considered in the Critical Shear Displacement Theory. A deeper research on the effects of load redistribution in slab bridges and how it affects the measured strains is still pending and requires further testing of slabs under cyclic loading.

8 SUMMARY AND CONCLUSIONS

Some of the bridges that are currently in service need to be evaluated to determine if their actual capacity is sufficient for the current traffic loads. For this purpose, in the Netherlands different levels of assessment are used. One of the highest levels used for assessment is proof load testing. With a proof load test it can be shown experimentally in the field that a bridge is suitable for the traffic loads it is subjected to. To show that a given bridge is safe in service, the target load for the test and the stop criteria required during the test need to be determined during the preparation stage. The stop criteria are defined as the structural responses that are not allowed to be exceeded during the test. If a stop criterion is exceeded, further loading is not permitted and the test should be terminated.

A review of the available acceptance and stop criterion present in current guidelines and codes was carried out. Special attention was paid to the stop criterion from the German Guideline. The conclusion from the literature review was that it is necessary to develop a stop criterion for shear. This stop criterion should have a theoretical basis.

A theoretical model that could predict the behavior of slab bridges in shear lies at the basis of the developed stop criterion. The Critical Shear Displacement Theory was chosen, as it is based on the different shear-carrying mechanism. Since reinforced concrete slabs can be considered as wide reinforced concrete beams without shear reinforcement, the Critical Shear Displacement Theory was considered suitable for the development of a stop criterion.

The measured response for the stop criterion is the strain at the bottom of the monitored member. The advantage of monitoring strains is that sensors can easily be applied to the bottom of the cross-section and monitored in real-time during a proof load test.

The ultimate shear capacity determined with the Critical Shear Displacement Theory is associated with the corresponding sectional moment. Flexural analysis is used to determine the strain at the bottom of the cross-section. This strain is used for the development of the stop criterion. Here it is assumed that the beam, slab or bridge has sufficient flexural reinforcement, so that shear failure occurs before yielding of the steel. The strain caused by the permanent loads is then subtracted from the calculated strain to form the proposed limiting strain for the stop criterion.

To verify the validity of the proposed stop criterion, the results of two experiments on two different beams were used. RSB03A was sawn from an existing bridges and subjected to a cyclic loading protocol. The beam failed in flexural shear. P804B was cast in the laboratory, tested under a stepwise monotonic loading protocol, and failed in shear. For both experiments, the proposed stop criterion was exceeded and showed good performance. As such, it is a promising result for the application to field testing.

Nevertheless, it is still necessary to continue studying the margin of safety provided by this stop criterion with further experiments. Moreover, research regarding the effects of load redistribution in slabs and its implications for the proposed stop criterion is necessary. More experimental results, especially on slabs under cyclic loads, are required to confirm the validity of the proposed stop criterion before it can be included in code provisions for the proof load testing of shear-critical bridges.

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Development of a Stop Criterion for Load Tests based on the Critical Shear Displacement Theory

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Content

1. INTRODUCTION

The evaluation of the capacity of existing bridge is an important aspect related to the safety of the users of those bridges. For this evaluation various methods are actually used, one of those is proof loading in which a target load representative of the factored live load of the bridge is used in order to evaluate the actual capacity of the bridge (Lantsoght, 2017). During the test the response of the bridge to the applied load has to be monitored, stop criteria is one of the ways in which the effects of the loads applied during the test could be controlled (Lantsoght, 2017).

This report will present the process followed for the development of a strain based stop criterion based on the Critical Shear Displacement Theory. At first all equations and the procedure for developing the proposed stop criterion are presented and then the evaluation of two beam tests is presented.

2. PROCEDURE FOR THE THEORETICAL DERIVATION OF A STRAIN BASED STOP CRITERION

2.1.Critical Shear Displacement Theory

The development of the stop criterion will begin with the prediction of ultimate shear capacity of a beam without shear reinforcement based on the model proposed by the Critical Shear Displacement Theory (Yang, 2017; Yang, 2016; Yang, 2014). This theory uses the displacement at which a flexural shear crack develops as the lower bound for the shear capacity. The theory uses the following shear transfer mechanisms produced in a flexural crack:

- Direct Shear Transfer
- Aggregate Interlock
- Dowel Action

Figure 10 Free body of a flexural shear crack with three main shear transfer mechanisms shows a free body diagram of these shear transfer mechanisms:

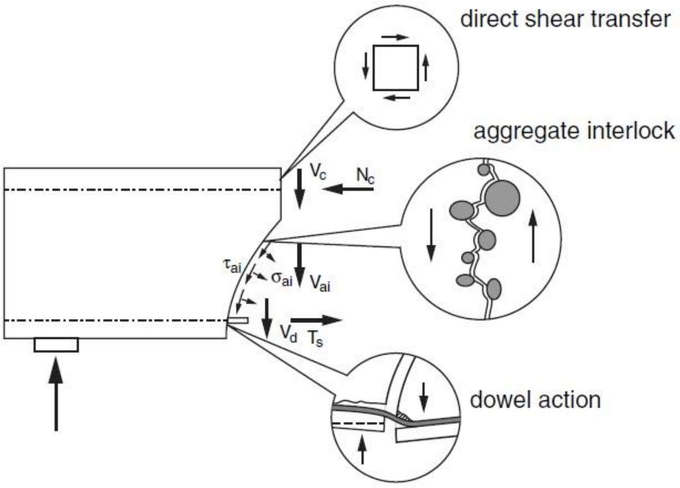


Figure 10 Free body of a flexural shear crack with three main shear transfer mechanisms

Each one of the mechanisms contributes to the whole shear bearing capacity of a beam. The contribution of each one of the components is calculated using the following equations:

- Direct shear transfer

$$V_c = \frac{d - s_{cr}}{d + 0.5s_{cr}} V \qquad (10)$$

V_c = shear force transferred in the compression zone

d = effective depth of the element

s_{cr} = height of the major crack, expressed with equation (2)

$$s_{cr} = [1 + \rho_s n_e - \sqrt{2\rho_s n_e + (\rho_s n_e)^2}]d \qquad (11)$$

ρ_s = longitudinal reinforcement ratio

n_e = ratio between elastic moduli of steel and concrete

- Dowel Action

$$V_d = 1.64 b_w Ø^3 \sqrt{f'c} \qquad (12)$$

V_d = shear force transferred by dowel action

b_w = width of the structural member

$Ø$ = rebar diameter

f'_c = concrete compressive strength

- Aggregate Interlock

$$V_{ai} = f'c^{0.56} s_{cr} b \frac{0.03}{w_b - 0.01}(-978\Delta^2 + 85\Delta - 0.27) \qquad (13)$$

V_{ai} = shear force transferred by aggregate interlock

w_b = crack width at the bottom of the crack, calculated with equation (5)

$$w_b = \frac{M}{zA_sE_s} l_{cr,m} \qquad (14)$$

M = cross sectional bending moment

z = length internal level arm

A_s = area of rebars

E_s = elastic modules of steel

$l_{cr,m}$ = spacing of two neighboring major cracks, calculated with equation (6)

$$l_{cr,m} = \frac{s_{cr}}{k_c} \qquad (15)$$

k_c = slope of the stress line, usually with a value of 1.28

$$\Delta = \frac{d}{29{,}800} + 0.005 \le 0.025mm \tag{16}$$

Total ultimate shear capacity calculated with the Critical Shear Displacement Theory:

$$V_{CSDT} = V_C + V_{ai} + V_d \tag{17}$$

The procedure to obtain the ultimate shear capacity is to start with a given value of V and calculate the V_{CSDT}, then iterate the V until V and V_{CSDT} are the same.

2.2.Moment curvature diagram

Any beam with a load applied on its span will develop both shear and bending forces and stresses. The aim of the moment curvature diagram is to describe the behavior of the beam in flexure.

For determining the moment and curvature at yielding, a parabolic stress-strain relationship is used as the one proposed by Thorenfeldt (MacGregor and Wight 2005).

2.3.Determination of strain at the bottom of the concrete

Once the shear force is determined using equations (1), (3) and (4). The bending moment produced by this shear force is determined by the following equation:

$$M_{CSDT} = V_{CSDT} \times a \tag{18}$$

Using the bending moment and the moment curvature diagram, the curvature produced by the bending moment M_{CSDT} should be calculated using the Moment curvature diagram previously calculated. For this an interpolation should be done using the points in which M_{CSDT} is located on the graph. This could be seen in Figure 11

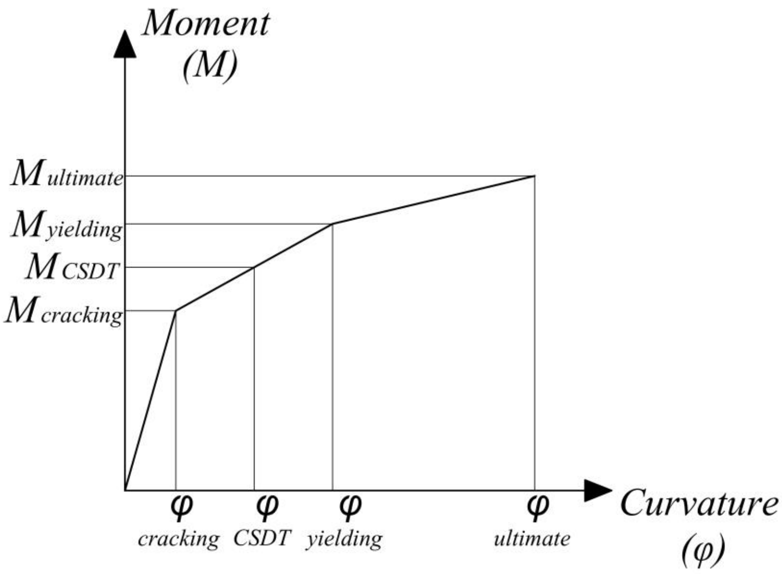


Figure 11 Moment Curvature diagram showing M_{CSDT} and φ_{CSDT}

Next the following equations show the procedure in order to find the strain at the bottom of the beam that will be used as the stop criterion, for this calculations Thorenfeldt's parabola is used in order describe the non-linear behavior of concrete:

Using equilibrium of forces between compression and tension as it could be seen in Figure 12:

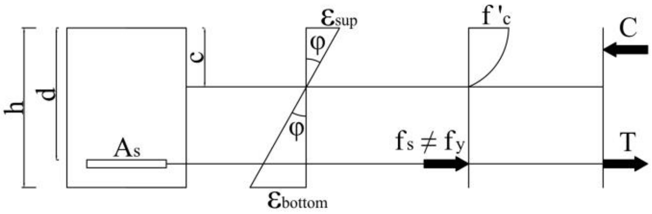


Figure 12 Stress-strain relationship of a cross section showing forces equilibrium

The following procedure has to be followed in order to calculate the limit strain of the proposed stop criterion, a parabolic stress-strain relation is also assumed for this calculations:

$$T = C$$

$$T = A_s f_s$$

$$C = \beta_1 f'_c \times b \times c$$

$$\beta_1 = \frac{\ln(1 + \varepsilon / \varepsilon_0)^2}{\varepsilon / \varepsilon_0}$$

$$f_c = \frac{0.9 f'_c\, n(\varepsilon/\varepsilon_0)}{n\text{-}1 + (\varepsilon/\varepsilon_0)^{nk}}$$

$$\varepsilon_0 = \frac{f'_c}{Ec} \times \frac{n}{n\text{-}1}$$

$$f_s = \varepsilon_s Es$$

$$\varepsilon_s = \varphi(h\text{-}c)$$

$$\varepsilon_c = \varepsilon_s \times \frac{c}{h\text{-}c} \qquad (19)$$

$$\varepsilon_c = \varepsilon_s \times \frac{c}{h\text{-}c} \qquad (20)$$

$$A_s \varphi(h\text{-}c) Es = \beta_1 f_c \times b \times c \qquad (21)$$

To solve equation (21) the value of c is iterated until the equilibrium between T and C is reached.

Then for the stop criterion the following equation is the one to be used:

$$\varepsilon_{\lim,CSDT} = \varepsilon_{c,bot} - \varepsilon_{c0} \qquad (22)$$

with ε_{c0} the strain caused by the permanent loads.

3.BEAM EXPERIMENTS

3.1.RSB03A

The Ruytenschildt Bridge was tested to collapse in August 2014, as part of the test four beams were sawn from the bridge(RSB Stop Criteria). One of these beams was RSB03A, which had a length of 6 meters and a width of 1000 mm approximately. The cross section of the beam could be seen in Figure 13 and Figure 14 shows the reinforcement ratio of the beam.

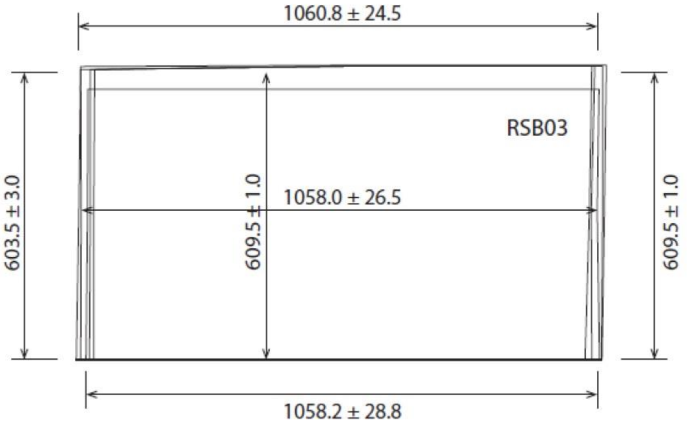


Figure 13 Cross section of beam RSB03A

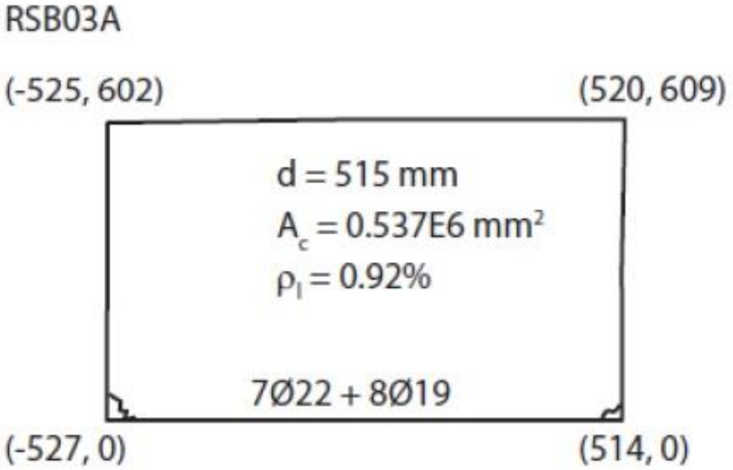


Figure 14 Reinforcement ration of beam RSB03A

The cylinder compressive strength of the concrete used for the beam had a value of f'_c = 52,2 MPa. And the reinforcement was of plain bars with a yield strength f_y = 282 MPa. The layer of asphalt on the beam was only removed in the places at which loads are applied. In Figure 15 the test setup could be seen, including the points of load appliance and supports.

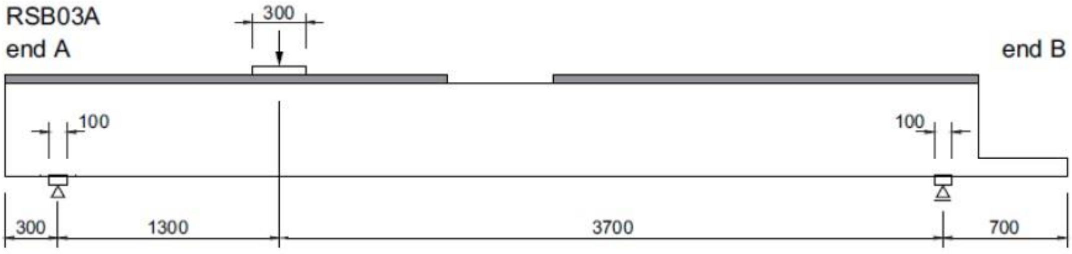


Figure 15 Test setup, position of loads and supports for beam RSB03A

For monitoring the beam during the test, 6 lasers for measuring deflections were placed among the beam and 8 LVDTs were placed as well on the sides of the beams for measuring horizontal deformations.

Figure 16 shows the loading scheme used for the test on beam RSB03A.

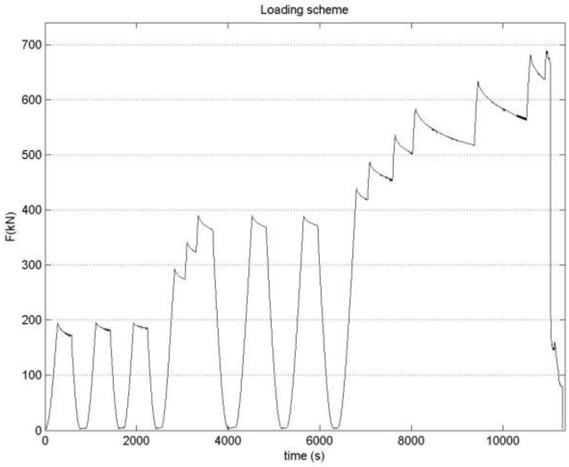


Figure 16 Loading scheme for beam RSB03A

Figure 17 shows a picture of the cross section of RSB03A, were the reinforcement distribution could be seen among the beam span.

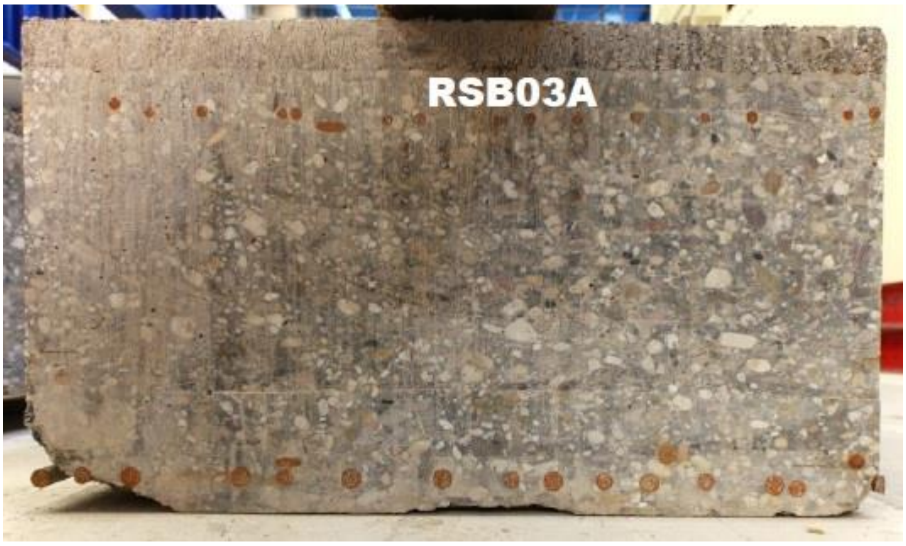


Figure 17 Cross section of the sawn cut of RSB03A

The beam was tested until failure using the loading protocol shown in Figure 16. This beam showed an inclined crack when it failed. This is typical of a flexural shear failure (rultenshildtbrug beam), this could be seen in figure 10.

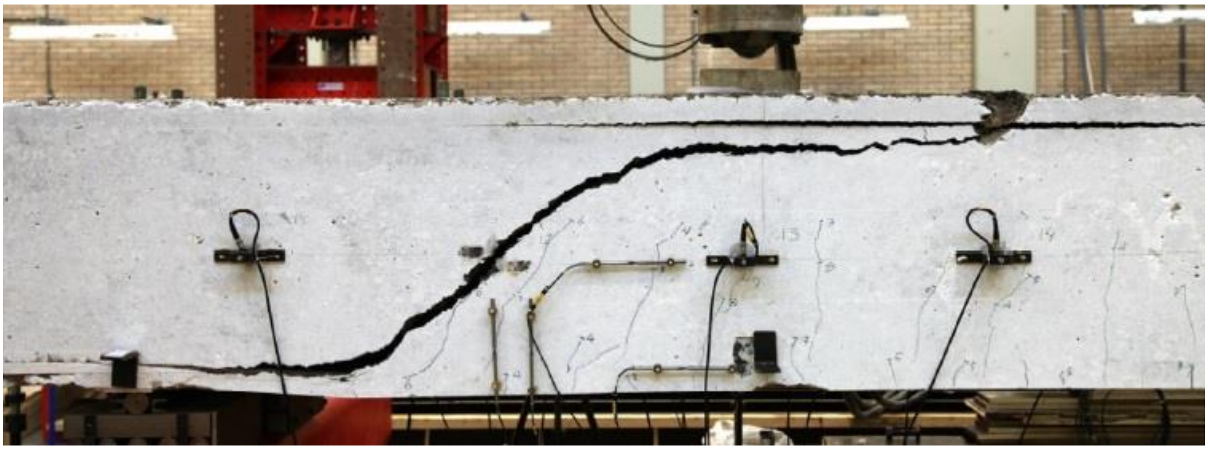
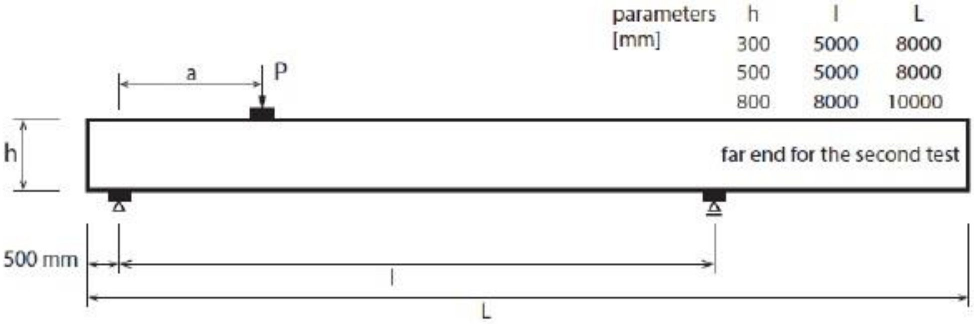


Figure 18 Failure of beam RSB03A

3.2.P804B

Beam P804B was taken from a series of experiments carried out on 10 meter length beam. The beam has a cross section of 800 mm height by 300 mm width. The concrete compressive strength of the beam was f'_c = 63,51 MPa, the yield strength of the reinforcement bars was f_y = 296,8 MPa. Figure 19 shows the test setup scheme for the tests carried out on beam P804.



parameters [mm]	h	l	L
	300	5000	8000
	500	5000	8000
	800	8000	10000

Figure 19 Test setup scheme the whole P804 tests

During this whole test in total 16 LVDTs and 4 lasers were placed among the beam in order to take various measurements during the test.

Figure 20 shows the loading protocol followed in the test of beam P804B.

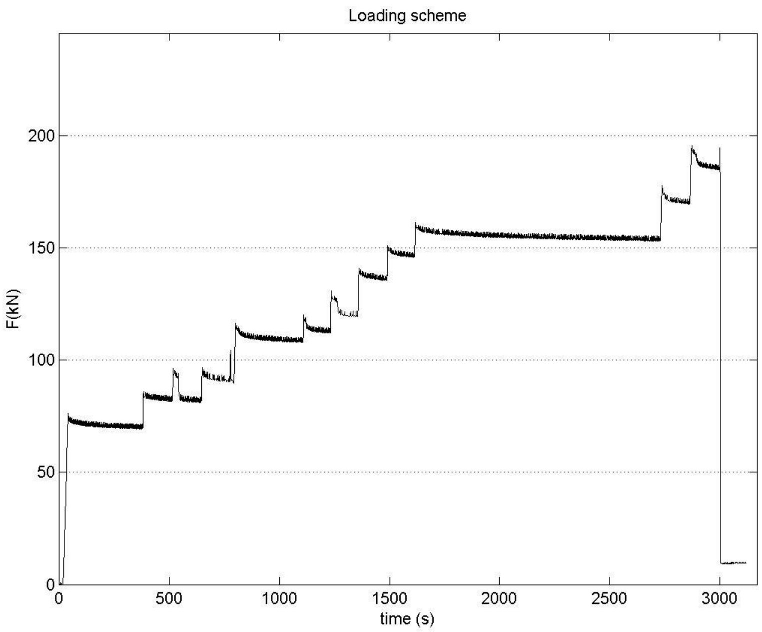


Figure 20 Loading protocol for the test on beam P804B

The beam was tested and showed a shear failure as shown in Figure 21.

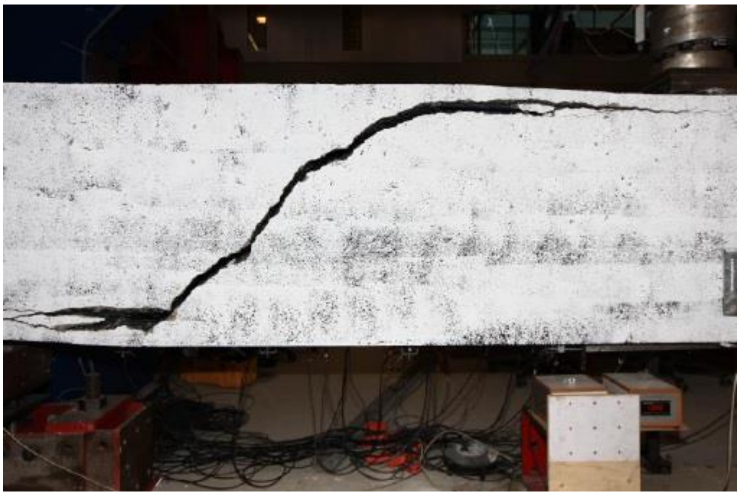


Figure 21 Failure of beam P804B after testing

4.CALCULATION OF PROPOSED STOP CRITERION

For beams RS03A and P804B the stop criterion proposed in this report will be calculated, in order to compare it with the obtained results.

4.1.Calculations for beam RSB03A

Calculation of ultimate shear capacity of the beam using the critical shear displacement theory:

- Contribution by Dowel Action using equation (3).

$$V_d = 133{,}9\mathrm{k}N$$

- Contribution by Aggregate Interlock using equation (4).

$$V_{ai} = 316{,}64kN$$

- Contribution by Direct Shear transfer using equation (1).

$$V_c = 108{,}98kN$$

Using equation (7) the total shear capacity of RSB03A is then calculated.

$$V_{CSDT} = 559{,}50kN$$

The moment-curvature diagram for RSB03A is calculated using equations from (8) to (22), and then is shown in Figure 22.

Table 4 shows the values of each point on the moment curvature diagram:

Table 4 Moment and curvature at each point of the Moment-Curvature diagram for beam RSB03A

Point on the Diagram	Moment (kN-m)	Curvature (/mm)
Cracking	290,23	$4{,}98 \times 10^{-7}$
Yielding	653,58	$4{,}00 \times 10^{-6}$
Ultimate	709,07	$7{,}00 \times 10^{-5}$

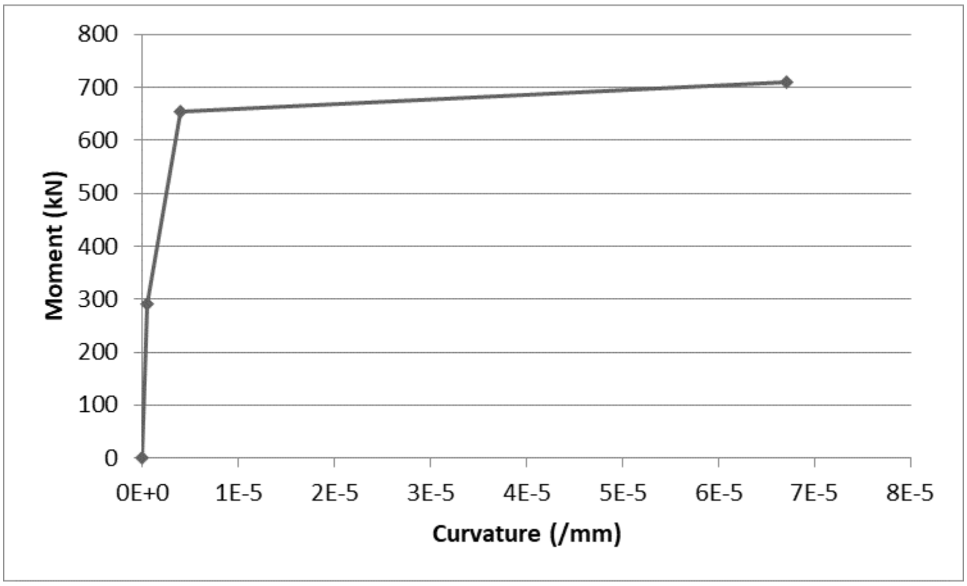


Figure 22 Moment curvature diagram for beam RSB03A

The moment corresponding to the total shear capacity determined with the Critical Shear Displacement Theory is calculated using equation (23), in this case the shear span is assumed to be 1000 mm, since the LVDTs are placed covering a distance of 400mm to 600mm under the loading point that is located at 1300mm (rultenschildtbrug beam)

$$M_{CSDT} = 559{,}50 kN\text{-}m$$

This moment is located in a point between the moment of cracking and the moment of yielding determined in the moment curvature diagram.

To find the curvature corresponding to M_{CSDT} an interpolation is made using the diagram shown in Figure 22. The corresponding curvature is:

$$\varphi_{CSDT} = 3{,}112 \times 10^{-6} / mm$$

Solving equation (25) by finding the value of c by iteration.

$$c = 248{,}8mm$$

This value of c is the replaced into equation (24) to get the strain calculated at the bottom of the cross section at a span of 1000mm.

$$\varepsilon_c = 774{,}22\mu\varepsilon$$

Then applying the equation (22) with $\varepsilon_{c0} = 17\mu\varepsilon$

$$\varepsilon_{\lim,CSDT} = 757\mu\varepsilon$$

4.2.Calculations for P804B

Calculation of ultimate shear capacity of the beam using the critical shear displacement theory:

- Contribution by Dowel Action using equation (3).

$$V_d = 39,26\text{k}N$$

- Contribution by Aggregate Interlock using equation (4).

$$V_{ai} = 107,32kN$$

- Contribution by Direct Shear transfer using equation (1).

$$V_c = 42,69kN$$

Using equation (7) the total shear capacity of RSB03A is then calculated.

$$V_{CSDT} = 189,27kN$$

The moment-curvature diagram for P804B is calculated using equations from (8) to (22), and then is shown in Figure 23.

Table 5 Moment and curvature at each point of the Moment-Curvature diagram for beam P804B

Point on the Diagram	Moment (kN-m)	Curvature (/mm)
Cracking	186,87	$3,47 \times 10^{-7}$
Yielding	378,58	$2,82 \times 10^{-6}$
Ultimate	411,65	$5,19 \times 10^{-5}$

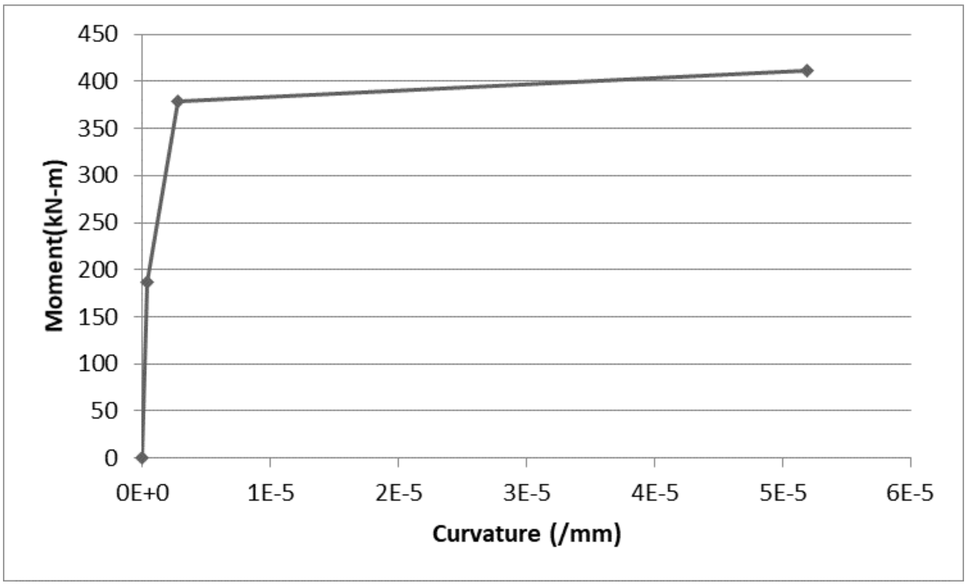


Figure 23 Moment Curvature diagram for beam P804B

The moment corresponding to the total shear capacity determined with the Critical Shear Displacement Theory is calculated using equation (23). The value was calculated at a shear span of 2000mm.

$$M_{CSDT} = 378,54 kN\text{-}m$$

This moment is located in a point between the moment of cracking and the moment of yielding determined in the moment curvature diagram.

To find the curvature corresponding to M_{CSDT} an interpolation is made using the diagram shown in Figure 22. The corresponding curvature is:

$$\varphi_{CSDT} = 2,824\times 10^{-6} / mm$$

Solving equation (25) by finding the value of c by iteration.

$$c = 321,85 mm$$

This value of c is the replaced into equation (24) to get the strain calculated at the bottom of the cross section at a span of 1000mm.

$$\varepsilon_c = 908,81 \mu\varepsilon$$

Then applying the equation (22) with $\varepsilon_{c0} = 45\mu\varepsilon$

$$\varepsilon_{\lim,CSDT} = 863\mu\varepsilon$$

5.EVALUATION OF PROPOSED STOP CRITERION

Table 6 shows the values obtained by the proposed stop criterion in percentage of the total load applied during the test; it also shows a comparison with the strain based stop criterion proposed by the German Guideline.

Table 6: Comparison between proposed stop criterion and German Guideline stop criterion

Beam	RSB03A	P804B
% load exceeded proposed criterion	80%	61%
% load exceeded Daftsb	83%	56%
% time exceeded proposed criterion	77%	40%
% time exceeded Daftsb	66%	26%

Figure 24 shows the strain load graph of beam RSB03A, showing the strain and load at which the stop criterion is exceeded.

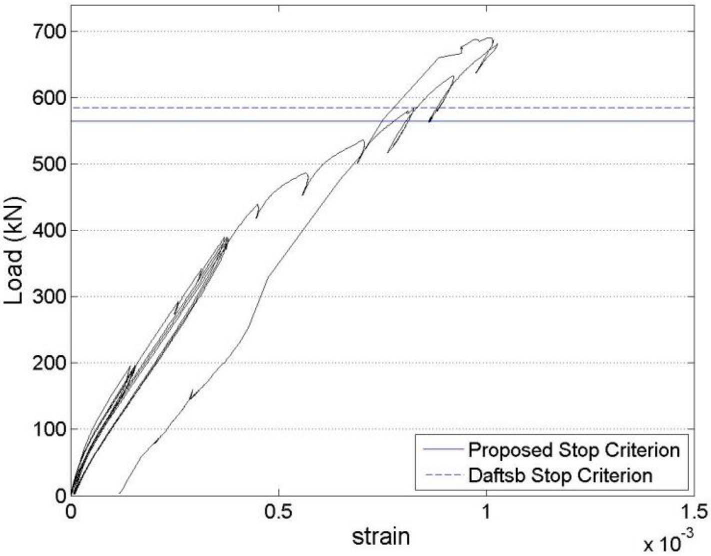


Figure 24 Load strain graph for RSB03A showing proposed stop criterion

Figure 25 shows the strain load graph of beam P804B, showing the strain and load at which the stop criterion is exceeded.

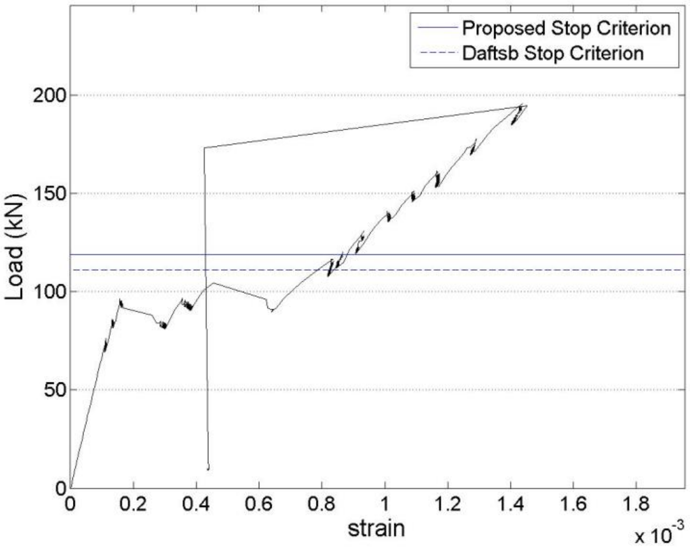


Figure 25 Load strain graph for P804B showing proposed stop criterion

Figure 26 shows the strain time graph of beam RSB03A, showing the strain and time at which the stop criterion is exceeded.

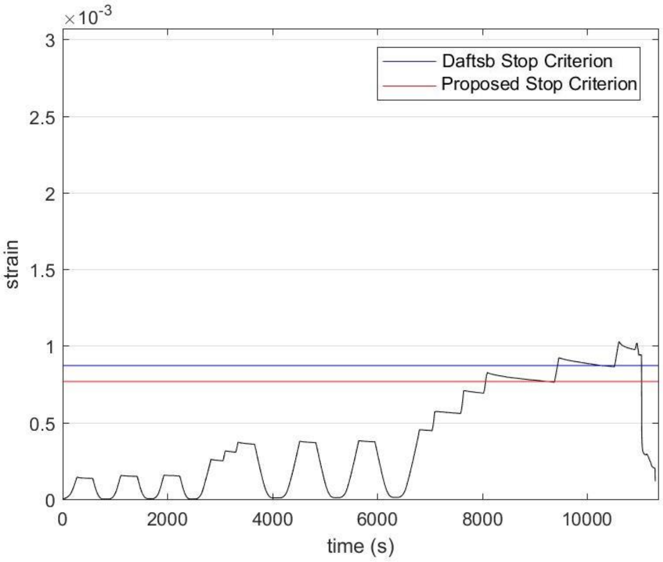


Figure 26 Strain time graph for RSB03A showing proposed stop criterion

Figure 27 shows the strain time graph of beam P804B, showing the strain and time at which the stop criterion is exceeded.

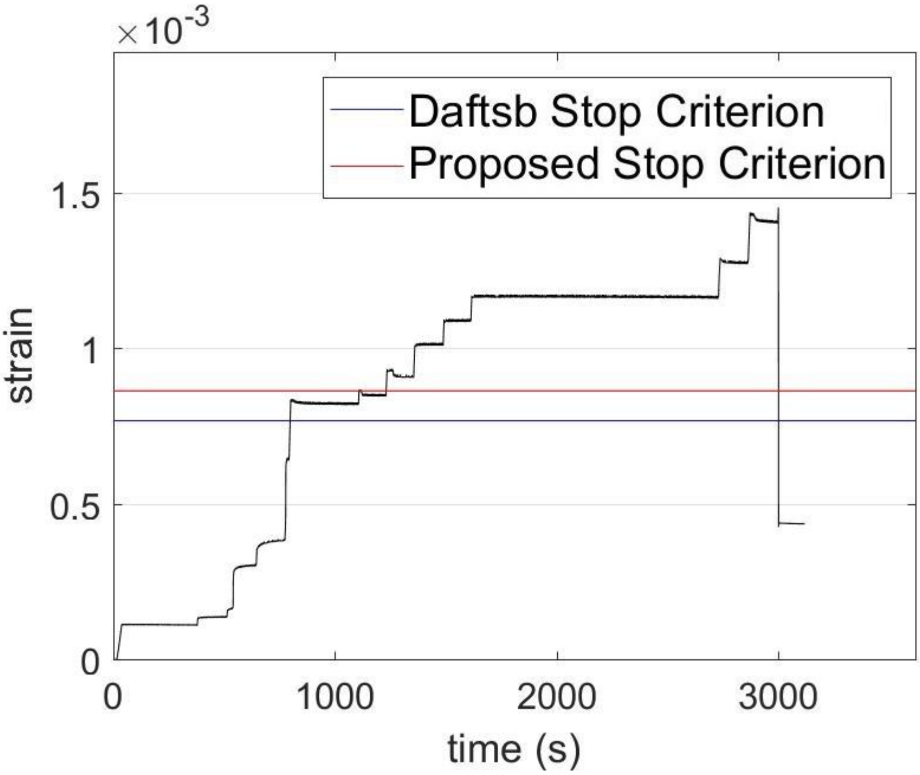


Figure 27 Strain time graph for P804B showing proposed stop criterion

The proposed stop criterion in both cases will show sign of an imminent failure of the beam during testing, even though these two test don’t show a fixed target load for tests because RSB03A is exceeded around 80% of the failure loading, but P804B is exceeded around 60% of the failure loading.

6.SUMMARY AND CONCLUSION

6.1.Development of a strain based stop criterion

This report presents the procedure to be followed to calculate the proposed stop criterion based on the Critical Shear Displacement Theory. The model prediction proposed by the theory for the ultimate shear capacity of a beam without shear reinforcement is used as well as reinforced concrete theory related to flexural behavior of beams. Then the procedure is applied to determine the target strain for shear tests on two beams. The calculations are shown step by step and finally a comparison is made between the results obtained with the proposed stop criterion and the strain based stop criterion of the German Guideline.

Measurements when using the proposed criterion should be taken at the exact distance were the calculations are made.

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8.APPENDIX A

This appendix presents the Matlab code that was used for the development of the proposed stop criterion.

```
%DETERMINATION OF CRITICAL SHEAR DISPLACEMENT
%Using the equations presented by Yang, Y the following script is developed
%for the evaluation of shear capacity for different beams.
clear all
epsilon = 0.001;

%Input data
d = input('Effective depth in mm: ');
ne = input('Ratio Es/Ec: ');
bw = input('Width in mm: ');
fy = input('fy in Mpa: ');
fc = input('fc in Mpa: ');
Es = input('Steel modulus of elasticity in Gpa: ');
Rebar = input('Rebar diameter in mm: ');
mvd = input('M/Vd: ');
kc = 1.28;
ps = input('Reinforcement ratio: ');
p=ps/100;
As = p*bw*d;
if (fc>28)
    B1 = 0.85-0.05*((fc-28)/7);
else
    B1 = 0.85;
end
a = (As*fy)/(0.85*fc*bw)
z = d-(a/2) %Length Internal level arm
scr = (1+p*ne-(2*p*ne+(p*ne).^2).^0.5)*d %Height of a major crack
lcr = scr/kc %Spacing between major cracks

%Force carried by dowel action in kN
vd = (1.64*bw*Rebar*(fc).^(1/3))/1000

%Force carried by compressive zone
vc = (d-scr)/(d+0.5*scr)


%Force carried by aggregate interlock
disp = 25*d/(30610*Rebar)+0.0022
if (disp<0.025)
    disp = 0.025;
end
V = 189.27;
vct=vc*V
M=V*d*mvd
wb=M/(z*As*Es)*lcr %Crack width at the bottom of a crack
vai=(fc^0.56)*scr*bw*(0.03/(wb-0.01))*(-978*disp^2+85*disp-0.27);
```

```
vai=vai/1000
Vt=vct+vd+vai
V = 1;
Vt = 0;


%iterations
while abs(V-Vt) > 0.01;
V=V+0.01;
vct=vc*V;
M=V*d*mvd;
wb=M/(z*As*Es)*lcr; %Crack width at the bottom of a crack
vai=fc^0.56*scr*bw*(0.03/(wb-0.01))*(-978*disp^2+85*disp-0.27);
vai=vai/1000;
Vt=vct+vd+vai;
end


M
wb
vai
Vt=vct+vd+vai;
Vt
V

sp = input('Shear span in mm: ');
M1 = V*(sp/1000)
%Interpolation between the values of cracking and yielding
Mcr = input('Moment at cracking stage: ');
My = input('Moment at yielding stage: ');
curvcr = input('Curvature at cracking stage: ');
curvy = input('Curvature at yielding stage: ');

%Interpolation between the values of cracking and yielding

m = (My-Mcr)/(curvy-curvcr);
curvm = ((M1-Mcr)/m)+curvcr;

%Thorenfeldt's parabola
ctrf = 1;
ntrf = 0.8+(fcpsi/2500);
eo = (fcpsi/Ec)*(ntrf/(ntrf-1));
es = curvm*(h-ctrf);
ec = (ctrf/(h-ctrf))*es;
eceo = ec/eo;
B1trf = (log10((1+(eceo)^2)))/(eceo);
fctrf = (0.9*fc*ntrf*(ec/eo))/((ntrf-1)+(ec/eo).^ntrf);
fstrf = Es*es*1000;
T = 2;
C = 1;

while T > C + epsilon
ctrf = ctrf+0.01;
```

```
ntrf = 0.8+(fcpsi/2500);
eo = (fcpsi/Ec)*(ntrf/(ntrf-1));
es = curvm*(h-ctrf);
ec = (ctrf/(h-ctrf))*es;
eceo = ec/eo;
B1trf = (log10((1+(eceo)^2)))/(eceo);
fctrf = (0.9*fc*ntrf*(ec/eo))/((ntrf-1)+(ec/eo).^ntrf);
fstrf = Es*es*1000;
C = B1trf*fctrf*bw*ctrf;
T = As*fstrf;
end
ec
es
C
T
```