The shear capacity of reinforced concrete members with plain bars

Yang, Yuguang; van der Veen, Cor; Hordijk, Dick; de Boer, A.

Publication date
2016

Document Version
Final published version

Published in
Structural Faults + Repair

THE SHEAR CAPACITY OF REINFORCED CONCRETE MEMBERS WITH PLAIN BARS

Y.Yang, C. van der Veen and D. Hordijk
Delft University of Technology
Stevinweg 1, 2628 CN, Delft
The Netherlands

A. de Boer
Ministry of Infrastructure and the Environment
Griffioenlaan 2, Utrecht
The Netherlands

KEYWORDS: Assessment of existing bridges, shear capacity, RC members without shear reinforcement, plain bars

ABSTRACT
Assessment of the capacity of the existing infrastructures has become more relevant in the recent years. With regard to the concrete bridges, the shear capacity of a large amount of existing concrete slab bridges reinforced with plain (smooth) bars are of concern.

However, it was argued that the shear formula that is currently adapted in the design codes are not fully calibrated by experiments on members with plain bars. The arguments are based on several experimental results found in literature from the 60s. At that time, the size effect on shear capacity of members without shear reinforcement was not widely recognized yet. Thus, the specimens applied in these experiments were mostly of small depth (d = 300 mm). In those experiments a significant improvement of the shear capacity was obtained in members reinforced by plain bars. The conclusions derived in those tests have to be further evaluated with specimens that represent realistic dimensions and other configurations of the slab bridge of concern. To serve that purpose, a series of shear tests have been carried out at the Stevin Lab in Delft University of Technology recently. A number of shear tests have been carried out on specimens reinforced by plain bars with low yielding strength. The heights of the specimens are 300 mm, 500 mm and 800 mm. The test results are compared with results of peer specimens with normal deformed bars with the same configurations (dimensions, concrete strength and reinforcement ratio). The experimental results are reported in this paper.

INTRODUCTION
The shear capacities of RC slab bridges decks without shear reinforcement is of concern in the Netherlands regarding the safety of the existing concrete bridges. Among the existing bridges in the Dutch highway system, there are more than 1000 concrete slab bridges built before 1976. They are reaching the design life at the moment. The shear capacity of these structures is of concern, because the shear design formula of the Dutch concrete code at that time predicted a higher shear capacity on such structures.

This was only realized after 1976, by then the code prediction was reduced to 80% of its previous prediction. The higher calculated shear capacity resulted in less effort to ensure the shear capacity of the bridge decks at that time. Moreover, at that time the size effect for structural members without shear capacity was not recognized yet. Therefore the shear formulas at that time were independent to the depth of the structure. Further researches revealed that the increase of the depth of the structure member will reduce the maximum allowable shear stress (Bažant and Kim, 1984, Walraven and Lehwalter, 1994, Walraven, 1978). Considering that the formula at that time was based on experiments of beams with less than 300 mm height, while most of the bridge slab decks have a minimum thickness of more than 500 mm. The actual capacities of these structures could be even worse.

In particular, there are about 750 bridges that were built before the year 1963. By then only plain bars with low yielding strength were available for bridge constructions. Those bridges consist of the largest portion among the shear critical concrete bridges in the Netherlands.

Nevertheless, researches have shown that despite the negative aspects of the shear formula mentioned above, many other aspects, which turn out to be beneficial to the shear capacity of the structural members, were ignored. In order to obtain a more accurate physical model for the shear behaviour of the concrete members, a large experimental research program has been carried out at Delft University of Technology in the last 5 years. The research resulted in a new physical model on the shear behaviour of concrete members without shear reinforcement (Yang, 2014, Yang et al., 2016b). One of the important aspects that might be ignored in the assessment of the existing concrete bridges is the effect of the plain bars to the shear capacity. In this paper, the research on the effect of plain reinforcing rebars to the shear capacity of concrete members without shear reinforcement is reviewed. In addition, the experimental research carried out at TU Delft on this effect is reported.

LITERATURE STUDY

In literature, very different results have been reported regarding the effect of the plain bars to the shear capacity of members without shear reinforcement. According to some researchers, the application of plain bars may increase the shear capacity of the member by more than 50% (Leonhardt and Walther, 1962, Kani et al., 1979). While in some other researches, the effect of plain bars to the shear capacity turns out to be limited (Yang et al., 2010, Yang et al., 2013, Regan, 2000, Lantsoght, 2013). Some of the researches are reviewed in this section.

In the experiments reported by Leonhards and Walther (Leonhardt and Walther, 1962), the shear capacity of beams reinforced by plain bars can be more than 150% higher than the counter parts with ribbed bars. The configurations of Leonhards' tests are given in Table 1. In these tests, different failure patterns were observed between the two test groups, see Fig. 1. In addition, from the photos indicated in (Leonhardt and Walther, 1962), it was suspected that the rebars that was used in Leonhards' tests were smoothened additionally to reduce the bond strength.

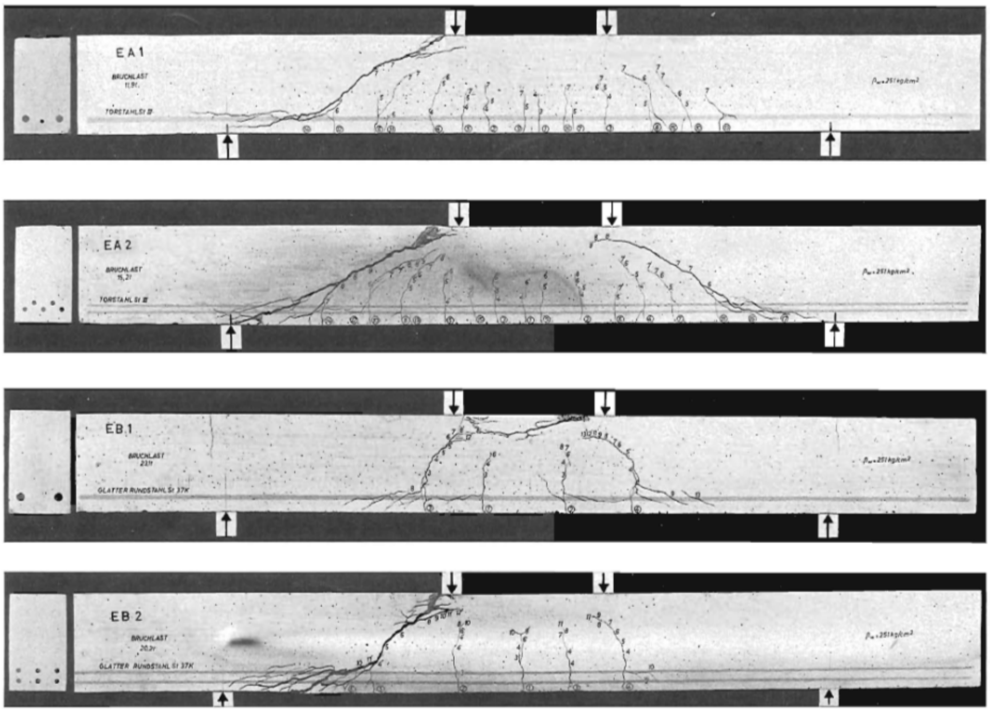

Fig. 1. Comparison of crack patterns for beams reinforced by plain bars and ribbed bars. EA: ribbed bars, EB: plain bars, for all the specimens, ρ_l = 1.9%, *h* = 320 mm.

Table 1. Test results Leonhardt's tests with varying reinforcement configuration. Translated from (Leonhardt and Walther, 1962).

Test No.	Reinforcement Configuration	D_{eq}[1] [mm]	ρ [%]	a/d [-]	d [mm]	$f_{cm,cube}$ [MPa]	P_u [kN]	V_u [kN]
EA 1	2Ø24 + 1Ø6	22.1	1.89	2.78	270	24.6	116.6	58.3
EA 2	2Ø14 + 3Ø16	15.1	1.88	2.78	270	24.6	149.0	74.5
EB 1	2Ø25	25.0	1.91	2.78	270	24.6	226.4	113.2
EB 2	5Ø14 + 1Ø16	14.4	1.88	2.78	270	24.6	198.0	100.0

[1] D_{eq} is the equivalent diameter of the reinforcement configuration, $D_{eq} = \sum D^2 / \sum D$. D is the diameter of each rebar.

A Similar conclusion was obtained by Kani (Kani et al., 1979). In Kani's test, the reduction of bond was achieved by adding a layer of vermiculite-cement mix between the ribbed bars and the concrete. The test series was designed to prove Kani's teeth model (Kani, 1964). As one of the first rational shear models the teeth model suggested that the poor bond strength between the plain bars and the concrete in the beams generates less breaking force to the teeth like structure formed by the flexural cracks, see Fig. 2. Accordingly, larger shear force is needed to break the concrete teeth.

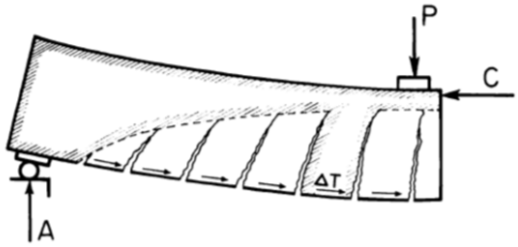

Fig. 2. Illustration of Kani's teeth model

For these tests, different theoretical interpretation was given by (Muttoni and Ruiz, 2008) and (Yang, 2014). Both theories assume that it is the formation of a critical crack in the shear span that results in the flexural shear failure. According to them, the higher shear capacity is due to the crack pattern of the tested beams. Because of the poor bond between the reinforcement and concrete, the flexural cracks are spaced more widely than that with ribbed bars. At failure, no flexural shear crack could form at the location where the compressive strut could be affected. According to (Yang, 2014), the spacing of the flexural cracks that can eventually form the critical flexural shear cracks are related to the depth of the structure and the bond strength of longitudinal reinforcement. When the depth of the structure is small, it was the bond strength that decides the crack spacing, that explains the phenomenon reported in (Leonhardt and Walther, 1962). For structures with larger depth, the effect of the beam depth on the crack spacing becomes more dominating. In that case, it is suspected that the effect of poor bond of the plain bars could not affect the global shear capacity anymore.

In the more recent tests reported by Regan (Regan, 2000), the effect of plain bars was already less pronounced. In his tests, the shear capacity of beams with plain bars was only about 20% higher than the reference tests with ribbed (deformed) bars. However, the number of tests reported in (Regan, 2000) was quite limited.

Moreover, the shear tests reported by (Yang et al., 2010, Yang et al., 2013) were carried out on specimens with plain bars. According to which, no significant increment of shear capacity was observed from these specimens in comparison with Eurocode predictions. However, no reference tests on specimens with ribbed bars were included in that research. In addition, in (Lantsoght, 2013), comparison on the shear capacity of one-way slabs reinforced with two different rebar types is reported, a similar conclusion was reported.

It has to be remarked that the tests in literature that showed a clear influence of rebar types are mostly found on specimens with depths less than 300 mm. Considering the strong effect of the beam height to the shear capacity, it is not clear if the conclusion can be extended to deeper beams. On the other hand, for the tests which showed limited effect from the plain bars, no reference tests were included or limited tests were carried out. It turns out that the assumption that beams reinforced by plain bars have higher shear capacity cannot be extended to the assessment of the existing concrete slab bridges directly. Further experimental evaluations are still needed.

EXPERIMENTAL PROGRAM

In order to investigate the influence of the rebar type to the structures with realistic dimensions and configurations, an experimental research program has been carried out at the Stevin Lab of Delft University of Technology. In total, 9 specimens were casted. The configurations of the specimens are listed in Table 2. The heights of the specimens are 300 mm, 500 mm and 800 mm. The thicknesses of most concrete slab bridge decks in the Netherlands fall in this range. The width of all the specimens is 300 mm. The length of the specimens is 10 m when their height is 800 mm. The other specimens are 8 m long. Since the deeper beams are more relevant for the assessment of the existing bridges, more specimens with h = 800 mm are included in the test program. The reinforcement ratio of the specimens is between 0.64 % and 1.18%, which is realistic for bridges. For each configuration listed, a specimen reinforced by plain bars and a control specimen with ribbed bars were casted. Fig. 3 indicates the photos of the two rebar types in the mould. For specimen P301, its control tests were shared with another test program carried out earlier (Yang et al., 2016a).

Table 2. Configurations of the test specimens, units [mm].

Specimen	***h***	***Rebar configuration***	***rebar type***
P301	300	3Ø20	plain
P501	500	5Ø20 (2 layers)	plain
R501	500	5Ø20 (2 layers)	ribbed
P801	800	3Ø25	plain
R801	800	3Ø25	ribbed
P802	800	6Ø20 (2 layers)	plain
R802	800	6Ø20 (2 layers)	ribbed
P803	800	2Ø20+4Ø25 (2 layers)	plain

Based on 150 mm cube tests, the mean compressive strength of the concrete mixture is f_{cm} = 63 MPa, which is comparable to the concrete strength obtained from cylinders drilled from several existing concrete bridges (Yang et al., 2010, Yang and den Uijl, 2011). The density of the concrete is 2430 kg/m^3.

Fig. 3. Photo of plain and ribbed bars in the mould

The expected yielding strength of the plain bars is f_{yk} = 240 MPa. It is expected that the rebars employed in this test program can represent the rebar type QR24 applied in the sixties suggested by (Rijkswaterstaat, 2013). Considering the possible changes regarding the production procedures of the structural steel in the last 50 years, several rebar samples were ordered in addition to the reinforcement cage. A simple tensile test was carried out on these samples with the tensile machine in the laboratory. Since the yielding strength of the rebar was of the most interest, only global elongation of the samples was measured. The typical stress – displacement relationship of a plain bar sample and a ribbed bar sample is given in Fig. 4. The yielding strength of the plain bars are comparable to that was measured from the rebars obtained from existing bridges according to (Yang et al., 2010). However, Fig. 4 shows that the yielding plateau from these plain bar samples is limited. Not all the rebar samples have been tested yet. Before further update, the yield strength of the plain and the ribbed bar are $f_{ym,1}$ = 296.8 MPa, and $f_{ym,2}$ = 583 MPa respectively according to Fig. 4.

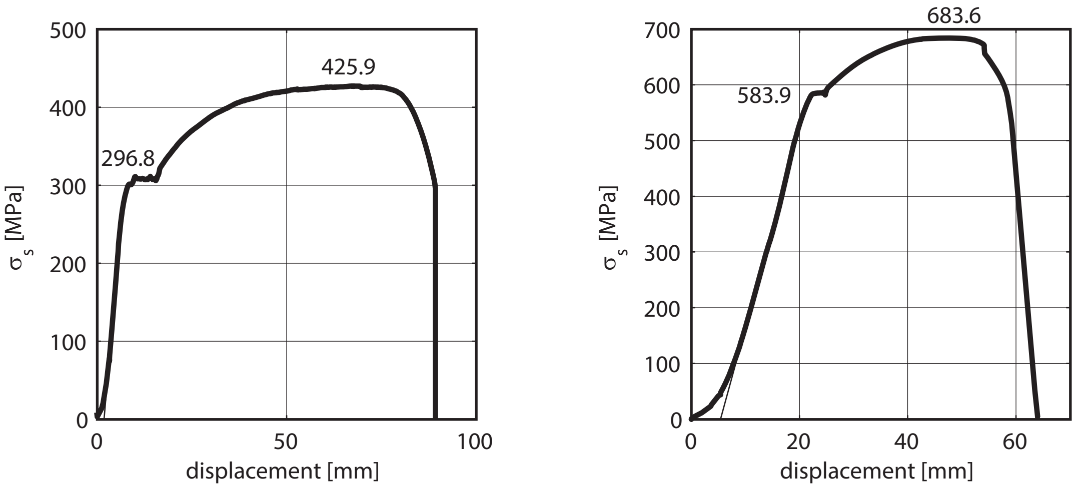

Fig. 4. Comparison of typical stress-displacement curve of plain bar and ribbed bar.

In the tests, the specimens were simply supported, and loaded with a single point load as illustrated in Fig. 5. The smaller centre to centre distance between the loading point and the support is defined as *a*, which is one of the main variables in the test series. The centre to centre distance between the supports is 8 m for 800 mm deep beams and 5 m for the rest. A larger support distance is to obtain larger shear slenderness ratio (*a/d*) for the 800 mm deep beams. The width of the load spreading plate at the loading point and the support is 100 mm. During the test, a part of the specimen at the far end was left as a cantilever. After the first test, the beam was turned so that the unloaded end could be used for an additional test on the same specimen.

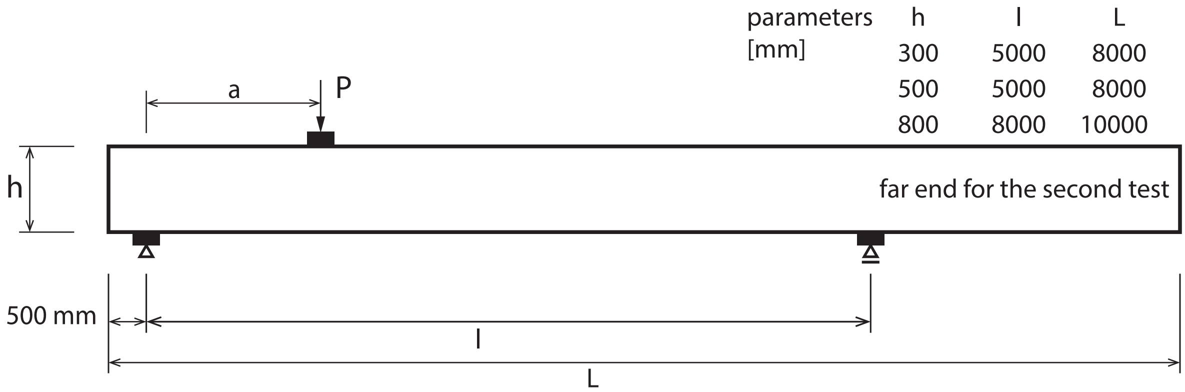

Fig. 5. Illustration of the test setup.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Up to the moment this paper is written, the experimental program has not finished completely. Not all the specimens listed in Table 2 were completely tested yet. In addition, because of the lower yield strength of the plain bars, not all the tests had shear failure. Therefore, in the test of some specimens with plain bars, the *a/d* was reduced in comparison with the reference tests. Nevertheless, the results of the executed tests with shear failure are summarized in Table 3.

In Table 3, P_u is the load level at the instant the flexural shear crack occurs in the tests. In most cases, this is equivalent to the peak load in the tests. V_u is the critical shear force at the cross section where the flexural shear crack formed. x_{crm} is the distance between the flexural shear crack and the support at the mid-depth, from which the contribution of self-weight to V_u is determined. In addition to the test results, the calculated shear capacity given by the Eurocode expression V_{Rdc} (Eurocode 2, 2004), and the Critical Shear Displacement theory (V_{csd}) proposed by Yang in (Yang, 2014, Yang et al., 2016b) are included as comparison. For the calculated value, the mean value of the material properties are used, no additional safety factors are included. For the Eurocode V_{Rdc} calculation, the factor C_{Rdc} = 0.15 was used according to (Yang et al., 2012).

Table 3. Summary of shear tests results on specimens with ribbed bars and plain bars (the shaded tests are specimens with plain bars).

No.	***a*** [mm]	***d*** [mm]	***a/d*** [-]	ρ_l [%]	f_c [MPa]	P_u [kN]	x_{crm}/d [-]	V_u [kN]	V_{ec} [kN]	V_{csd} [kN]
P301A2	600	265	2.35	1.19	62.8	124.0	1.20	113.7	92.2	120.0
A122B2*	750	271	2.77	1.16	62.8	139.1	1.38	122.6	94.6	115.5
A123A2*	800	270	2.96	1.16	62.8	139.0	1.16	121.3	94.5	112.5
P501A2	1250	455	2.75	1.15	62.8	175.0	1.64	137.3	141.8	178.1
P501B2	1000	455	2.20	1.15	62.8	202.0	1.31	168.2	141.8	196.5
R501A	2500	455	5.49	1.15	62.8	276.6	4.07	140.5	141.8	133.3
R501B1	1500	455	3.30	1.15	62.8	210.0	1.88	152.7	141.8	164.7
P801A3	1500	763	1.97	0.64	62.8	227.0	1.34	200.9	181.0	226.2
R801A	2000	763	2.62	0.64	62.8	212.0	1.78	173.6	178.1	200.8
P802A	2000	755	2.65	0.83	62.8	248.0	1.83	200.5	192.4	214.0
P802B	2000	755	2.65	0.83	62.8	208.0	1.82	170.5	192.4	214.0
R802A	2000	755	2.65	0.83	62.8	219.0	1.55	179.9	192.4	214.0
R802B	2000	755	2.65	0.83	62.8	268.0	1.82	215.5	192.4	214.0
P803A	2000	750	2.67	1.15	62.8	290.4	1.34	234.3	213.2	249.5
P803B2	2750	750	3.67	1.15	62.8	278.0	1.77	197.2	213.2	216.8

*the tests A122B2 and A123A2 are shear tests on beams reinforced by ribbed bars, they are shared with another test series reported in (Yang et al., 2016a).

In general, Table 3 does not show clear differences regarding the shear capacity of specimens with plain bars and the references. As an example, the shear capacity of the test pair P802A, R802A, and P802B, R802B are directly comparable. The four tests have the same configurations. The resultant shear capacities of the four tests are quite comparable. The capacity of P802A and P802B are not higher than R802A and R802B. Besides, the difference is within 20%, thus can be explained by the scatter of the tests. Similar conclusions can be drawn from most of the tests that are reported in Table 3.

In addition to the capacity, the load – deflection relationship of the two groups are compared in Fig. 6 and Fig. 7 respectively. Similar to the shear capacity, the four tests with identical configurations turns out to be rather comparable. The difference mainly lies in the peak load under which the drop of the load level occurred. The lower bond between the plain bars and the concrete did not have an effect on the global stiffness of the tested members either.

It has to be remarked that not all the tests are of the same *a/d* of the references. However, in all cases, the tests on members with plain bars had smaller *a/d* values than that with ribbed bars. According to (Yang, 2014, Yang et al., 2016b, Muttoni and Ruiz, 2008), smaller *a/d* values results in a higher shear capacity. Therefore, the difference regarding the loading positions will not be the reason that the shear capacity of the members with plain bars are reduced

In some of the tests, the peak load was much higher than the value of P_u reported in Table 3. In that case, the compression strut in that failure mode was not affected by the formation of the critical flexural shear crack. The final failure is then caused by the compression failure of the strut close to the loading point. The shear failure mode is shear compression failure (Yang, 2014). The test R802B was such example, see

Fig. 7. In that case, the value of P_u in Table 3 represents the load level when the unstable propagation of an inclined crack occurs along the tensile reinforcement and the compressive zone. A clear drop of the applied load was obtained in the load – deflection relationship in the test, which was clearly due to the opening of the flexural shear crack. Although further increase of the deflection could increase the load level again, and the actual maximum load was higher, because of the presence of the large inclined crack, the specimen was considered as unsafe (failure) by P_u. The different failure mode in the test R802B can be attributed to the different location of the inclined crack x_{crm}, see Table 3.

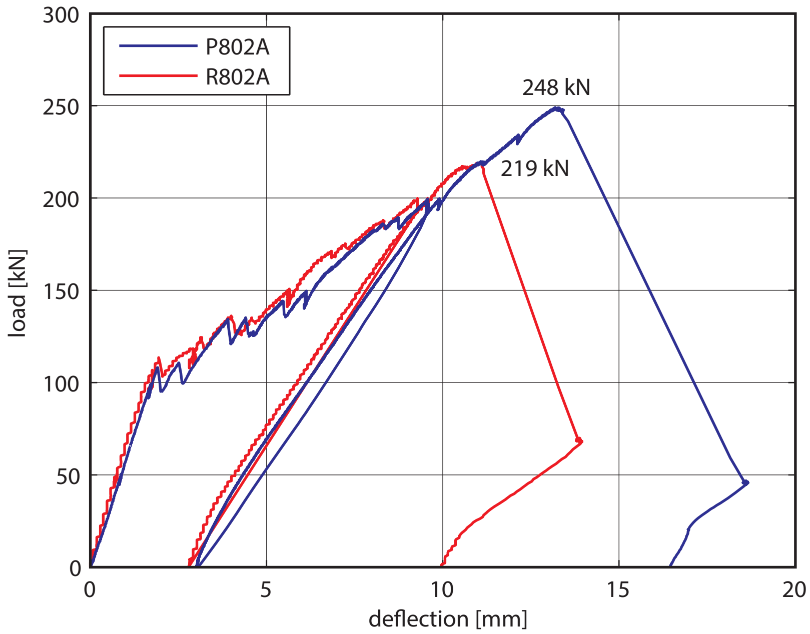

Fig. 6. Comparison of load – deflection relationships of P801A and R801A.

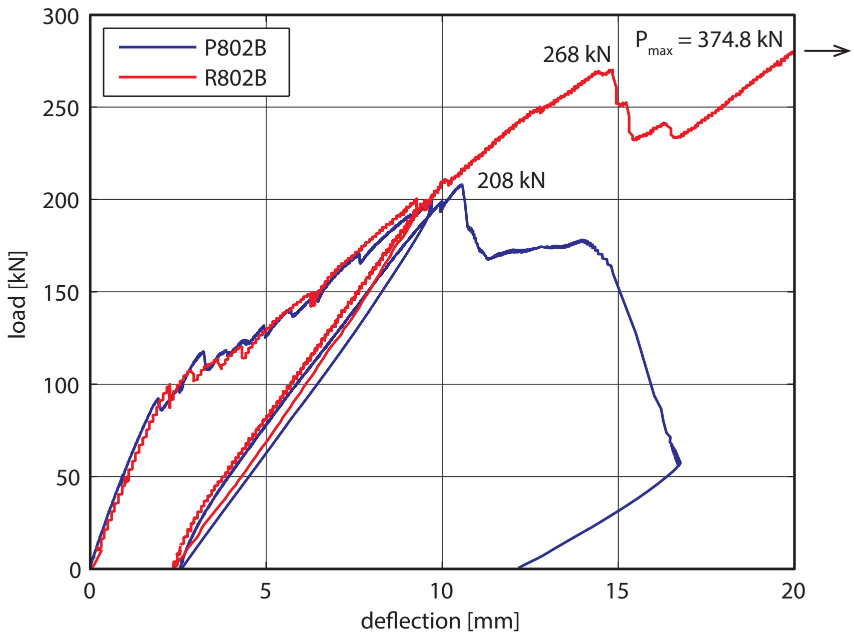

Fig. 7. Comparison of load – deflection relationships of P801B and R801B.

In comparison with the code provisions, Table 3 shows a reasonable agreement to the Eurocode V_{Rdc} expression. The mean value of V_u/V_{EC} from Table 3 was 1.07, with the coefficient of variation COV = 11.8%. In the case of the Critical Shear Displacement theory, V_u/V_{csd} = 0.92, with COV = 9.8%. Similarly, the comparison did not show a clear difference between members with plain bars and the references.

To sum up, in the test series presented in this paper, it turns out that the members reinforced by the plain bars do not have very different shear behaviour in comparison with that of normal ribbed bars. The lower bond strength of the plain bars compared to the deformed bars will not result in a change of shear failure behaviour of the test configurations in this study. As a result, one may conclude that it is not safe to increase the shear capacity of the existing concrete slab bridges reinforced with plain bars yet.

CONCLUSTIONS

This paper presents a study on the effect of the rebar type to the shear capacity of reinforced concrete members without shear reinforcement. In the Netherlands plain bars were widely applied as reinforcement before the sixties. In order to accurately evaluate the residual capacity of these structures, the effect of plain bars to the structural shear behaviour has to be investigated. Based on the results of a literature study, contradictory conclusions were obtained. Most of the tests results reported in the literature cannot be applied directly in the assessment of the existing bridges reinforced with plain bars. For these reasons, an experimental program was carried out at the Stevin lab of Delft University of Technology. The specimen depth, the concrete strength and the reinforcement ratio of the specimens in this research are comparable to that of the existing bridges. Shear tests were carried out on the specimens of the similar configurations but reinforced with plain bars or ribbed bars respectively. The comparison did not show a clear difference between specimens reinforced with plain bars and the reference group regarding the shear behaviour. In addition, it showed that the shear capacity of these specimens can be predicted with the theoretical models such as the Eurocode or the Critical Shear Displacement model with reasonable accuracy.

REFERENCES

BAŽANT, Z. P. & KIM, J.-K. 1984. Size Effect in Shear Failure of Longitudinal Reinforced Beams. *ACI Journal,* 81**,** 456-468.

EUROCODE 2 2004. NEN-EN 1992-1-1 Design of Concrete Structures: General Rules and Rules for Buildings.

KANI, G. N. J. 1964. The Riddle of Shear and Its Solution. *ACI Journal,* 61**,** 441-467.

KANI, M. W., HUGGINS, M. W. & WITTKOPP, R. R. 1979. *Kani on Shear in Reinforced Concrete,* Canada.

LANTSOGHT, E. 2013. *Shear in Reinforced Concrete Slabs under Concentrated Load close to Supports.* Ph.D, Delft University of Technology.

LEONHARDT, F. & WALTHER, R. 1962. Schubversuche an einfeldrigen Stahlbetonbalken mit und ohne Schubbewehrung. Deutscher Ausschuss für Stahlbeton.

MUTTONI, A. & RUIZ, M. F. 2008. Shear Capacity of Members without Transverse Reinforcement as Function of Critical Shear Crack Width. *ACI Structural Journal,* 105**,** 163-172.

REGAN, P. E. 2000. Aspects of diagonal tension in reinforced concrete *Structural Concrete,* 1**,** 119-132.

RIJKSWATERSTAAT 2013. Richtlijnen Beoordeling Kunstwerken, Beoordeling van de constructieve veiligheid van een bestaand kunstwerk bij verbouw, gebruik en afkeur.

WALRAVEN, J. C. 1978. The Influence of Depth on the Shear Strength of Lightweight Concrete Beams without Shear Reinforcement. Delft: Delft University of Technology.

WALRAVEN, J. C. & LEHWALTER, N. 1994. Size Effects in Short Beams Loaded in Shear. *ACI Structural Journal,* 91**,** 585-593.

YANG, Y. 2014. *Shear Behaviour of Reinforced Concrete Members without Shear Reinforcement - A New Look at an Old Problem.* Ph.D - thesis Dissertation, Delft University of Technology.

YANG, Y. & DEN UIJL, J. A. 2011. Report of Experimental Research on Shear Capacity of Beams Close to Intermediate Supports. Delft: Delft University of Technology.

YANG, Y., DEN UIJL, J. A., DIETEREN, G. & DE BOER, A. 2010. Shear Capacity of 50 Years Old Reinforced Concrete Bridge Deck without Shear Reinforcement. *the 3rd Congress of the International Federation for Structural Concrete.* Washington DC.

YANG, Y., DEN UIJL, J. A. & WALRAVEN, J. 2012. Shear Capacity of Reinforced Concrete Beams under Complex Loading Conditions. *the 9th fib International PhD Symposium in Civil Engineering.* Karlsruhe: Karlsruhe Institude of Technology.

YANG, Y., DEN UIJL, J. A. & WALRAVEN, J. C. 2013. Residual Shear Capacity of 50 years Old RC Solid Slab Bridge Decks. *International IABSE Conference: Assessment, Upgrading and Refurbishment of Infrastructures.* Rotterdam.

YANG, Y., VAN DER VEEN, C., HORDIJK, D. A. & DE BOER, A. 2016a. Investigation of vmin based on experimental research. *fib 2016.* Cape Town.

YANG, Y., WALRAVEN, J. & DEN UIJL, J. A. 2016b. The Critical Shear Displacement theory: on the way to extending the scope of shear design and assessment for members without shear reinforcement. *Structural Concrete,* in press.