SHEAR CAPACITY OF STEEL FIBRE REINFORCED CONCRETE COUPLING BEAMS

J. S. Kuang[1] and Bartlomiej Jan Baczkowski[2]

ABSTRACT

In tall buildings, reinforced concrete coupled shear-wall structures are commonly used to provide the resistance of lateral loading caused by wind and earthquake. Coupling beams connect shear walls along the height of the building and are normally subjected to very high bending and shear stresses. Shear strength of conventional reinforced concrete beams depends mainly on the cross-sectional dimensions rather than on the amount of steel reinforcement and is therefore limited by architectural design.

The use of reinforced steel-fibre-concrete in coupling beams is considered as a practical, yet innovative, solution to the problem of insufficient shear strength. The steel fibres in concrete can substantially improve shear behaviour of concrete beams. This paper presents the results of tests on large-scale steel fibre reinforced concrete (SFRC) coupling beams with span-to-depth ratios of 1, 1.5 and 2 under monotonic loading. Emphasis of the experiment is placed on the shear behaviour and shear strength of the tested beams. It has been shown from the tests that the shear capacity of SFRC coupling beams is much higher than that of conventional reinforced concrete ones.

KEY WORDS

steel fibre reinforced concrete, tall buildings, coupling beams, shear strength.

INTRODUCTION

Coupled shear wall is a shear wall pierced by openings such as doors or windows. If the openings are along a vertical line, the system can be represented by two or more shear walls connected by coupling beams at floor levels. Under lateral loading such as wind or earthquake, the shear is resisted by the shear walls while bending moment is carried by the individual shear walls and by a coupled action of axial forces between them.

Shear capacity of a reinforced concrete beam is normally limited to a certain value of shear stress by the design codes of structural concrete. The codes of practice in Britain, America and Europe, such as BS 8110, ACI 318 and EC2, all express the maximum shear stress as a function of compressive strength of concrete with the BS imposing an additional limit on shear stress regardless of the strength of concrete. The previsions are based mainly on statistical analyses of an immense amount of test data and therefore can generally guarantee a very high degree of conservatism in design.

---

[1] Assoc. Prof., Dept. of Civil Engrg., Hong Kong Univ. of Science & Technology, Clear Water Bay, Kowloon, Hong Kong, Phone +852 2358-7162, FAX +852 2358 -1534, cejkuang@ust.hk

[2] Ph.D. Candidate, Dept. of Civil Engrg., Hong Kong Univ. of Science & Technology, Clear Water Bay, Kowloon, Hong Kong, Phone +852 2358-8759, FAX +852 2358-1534, bartek@ust.hk

COUPLING BEAMS

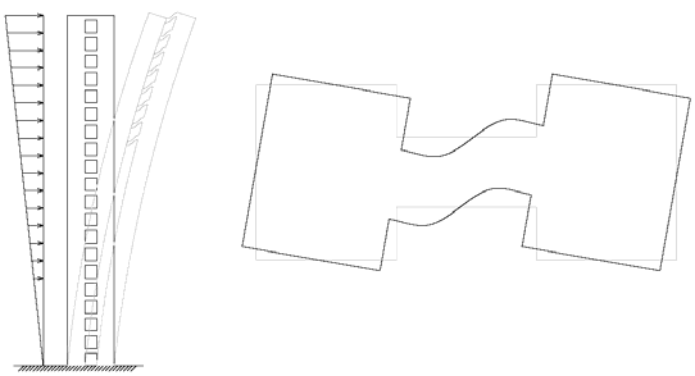
SHEAR CAPACITY OF CONCRETE BEAMS

The shear capacity of concrete beams specified in codes is usually expressed in terms of the maximum shear force allowed on a critical section, the influence of bending moments being neglected. The shear capacity is set based mainly on a statistical analysis of a large number of test results of simply supported concrete beams rather than on theoretical developments.

In fact, failure of a concrete element is generally initiated by the matrix fracture. It can be assumed that the matrix cracks along the path of principal compressive stresses. The mode of the ultimate failure of an element depends on its cracking pattern and is therefore based on the stress path rather than on its internal forces.

LOADING ON COUPLING BEAMS

Under lateral loading caused by wind or earthquake, shear walls of a tall building bend in flexure applying double curvature bending on the coupling beam. This produces strong shearing forces on the beam, equal to the combined moments on both wall panels divided by the clear span of the beam. The deformation of a coupling beam caused by indirect loading is depicted in Figure 1.



(a) (b)

Figure 1: Indirect Loading on Coupling Beam Causing Double Curvature Bending. (a) Coupled Shear Walls Subjected to Lateral Loading; (b) Deformation of Coupling Beam.

Increasing heights of constructed buildings as well as ever-high pressure on the construction cost control call for new engineering solutions as the old ones become obsolete. New types of coupling beams have been developed such as beams with embedded steel plates (Subedi 1989, Kuang and Cheng 2004). The beams with embedded steel elements are very strong; but the strength comes at a high price and the construction difficulty may also be raised. There are also many technical difficulties resulting from having to ensure a strong bond between steel and concrete.

The possibility of using steel fibres rather than steel plates to strengthen the beams is investigated. Description of the experimental programme follows.

EXPERIMENTAL PROGRAMME

DIMENSION AND REINFORCEMENT DETAIL OF SPECIMENS

Three large scale coupling beams are fabricated. The specimens have the same cross-sectional properties and differ in the span-to-depth ratios. Detailed dimensions and reinforcement details of the specimens are presented in Figure 2 and Table 1.

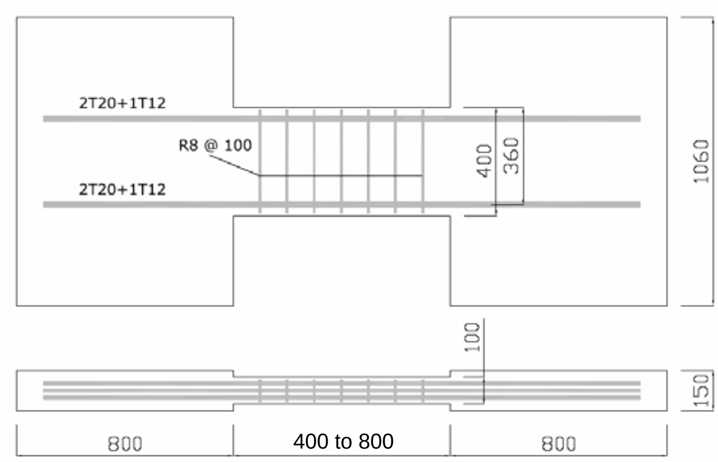


Figure 2: Dimensions and Reinforcement Details of Specimens

Table 1: Details of Coupling Beams

Specimen	Span (mm)	Depth (mm)	Width (mm)	Span-to-Depth Ratio	Longitudinal Steel Ratio ρ (%) ($A_s = A'_s$)	Transverse Steel Ratio ρ_v (%)
S-10/M	400	360	100	1.11	1.05	1.0
S-15/M	600	360	100	1.67	1.05	1.0
S-20/M	800	360	100	2.22	1.05	1.0

Longitudinal reinforcement of 1.05% detailed at the top and bottom of the beams, respectively, has been provided to avoid the flexural mode of failure, and the ratio of the transverse reinforcement in the form of stirrup is 1.0 %. This follows the design guidelines for concrete coupled shear wall buildings by CIRIA (Irwin 1984). In addition, sufficient amounts of longitudinal high-yield steel bears have also been provided in the wall panels.

MATERIALS

All the test specimens are made with steel fibre reinforced concrete due to its higher shear strength than that of conventional structural concrete. Even though it is rather well known as the first research project on shear properties of SFRC was started three decades ago (Batson et al. 1972), SFRC is only occasionally used in structural elements of buildings. In fact, steel fibre in concrete can significantly increase the shear strength of structural concrete (Lim et al. 1987, Casanova et al. 1994). It will be shown here that adding even a small amount of steel fibre (one percent by volume) can improve significantly fracture properties of concrete, thus improving ductility, overall behaviour in tension as well as element's performance in shear.

The fresh concrete for the specimens is supplied by a contractor and the aggregate size is limited to 10 mm in order for to avoiding fibre distribution problems in fresh concrete. Approximately one quarter of cement is replaced by fly ash and the water-to-cement ratio is 0.45. The mean cube compressive strength of concrete, f_{cu}, is 48.4 MPa. Approximately 80 kg of DRAMIX RL-45/50-BN steel fibre is added per cubic metre of concrete. Pure concrete is placed in a truck-mixer and then the fibres are added.

After strengthening of concrete, cores are taken from concrete to investigate the distribution of fibres. In addition, beam elements have been fabricated for testing of fracture properties of the SFRC.

In all the test specimens, longitudinal and transverse bars used are high-yield steel and mild steel, respectively.

TEST SETUP

There are two established methods for testing coupling beams. The first one applies shear directly (Kuang and Cheng 2004), while the other applies loading indirectly through rotation of the wall panels (Pauley 1969). In this paper, an innovative test setup for testing coupling beam shown in Figure 3 is introduced which is developed for the experimental programme. Both monotonic and reversed-cycling loading tests can be performed with this test setup. The test rig with a tested specimen is shown in Figure 4.

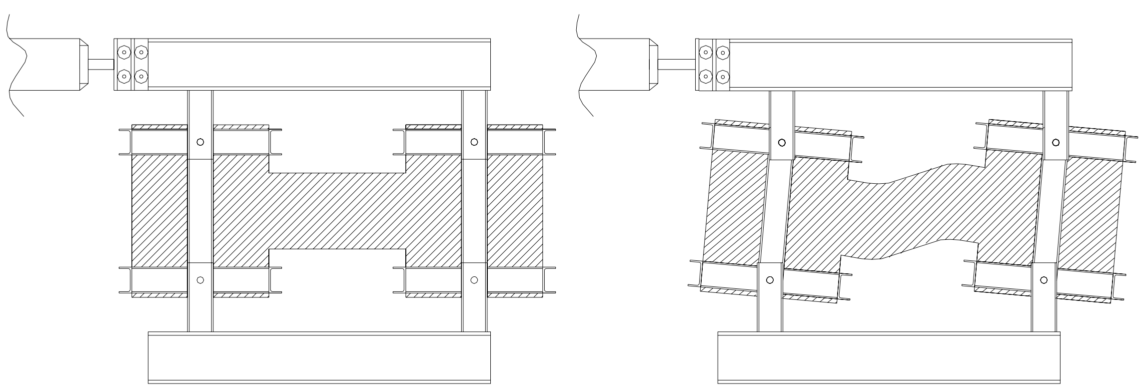


Figure 3: Schematic Representation of Test Setup

In the tests, a 1000-kN hydraulic actuator mounted onto a strong 1-m thick concrete reaction wall is employed to apply lateral loading at the top beam of the test rig, as shown in Figure 3. The loading is then distributed equally between the top hinges on the wall panels. The corresponding forces applied on the top hinges and the reaction forces on the bottom ones create same direction rotating moments on both panels. This flexes the beam in double curvature as shown on Figure 3. Strong steel struts connecting top and bottom hinges ensure equal rotation of wall panels.

Figure 4: Test Rig with Tested Specimen

The test setup is designed to allow for changing span-to-depth ratios while keeping a constant depth of the coupling beams. When a specimen with different beam span is to be tested, the hinges on the right side are simply mounted further away from the ones on the left side. This alleviates the necessity of considering the size effect.

INSTRUMENTATION

Strain gauges are installed on the longitudinal reinforcement at both top and bottom sides as well as on the chosen stirrups. Some gauges are also added to the test rig for performance control of the experiment. LVDTs are used to monitor the rotation of wall panels, vertical beam deflection and the distribution of the applied load. Moreover, high resolution digital images have also been taken throughout the tests to investigate crack patterns of the specimens and their fracture behaviours in general.

TEST RESULTS

OVERVIEW

In all test specimens, flexural cracks are developed at an early stage of loading and before the formation of shear ones. As the increase in loading, diagonal shear cracks are observed and then become predominant very soon and eventually lead to shear failure of the specimen. Cracking patterns on the shallowest specimen are shown on Figure 5.

SHEAR CAPACITY

Plots of the shear stress versus vertical deflection of the coupling beam specimens are shown in Figure 6. It is see that the shear capacity of the SFRC coupling beam with a low span-depth ratio is higher than that with a higher span-depth ratio. However, most of the current concrete design standards disregard the influence of span-to-depth ratios on the overall performance of an element in shear introducing a concept of a critical section instead. It is evident that there is a relation – especially prominent in case of deep beams.

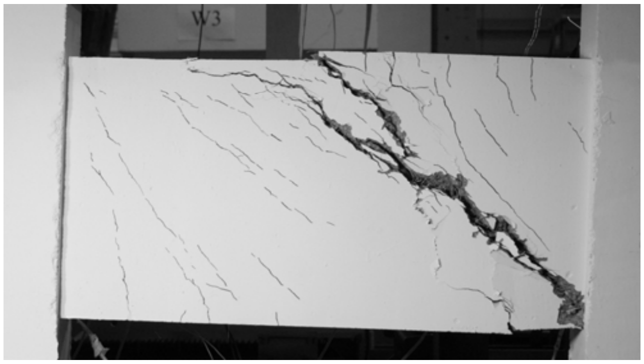


Figure 5: Crack pattern of Specimen S-20/M (Span-to-Depth Ratio = 2.22)

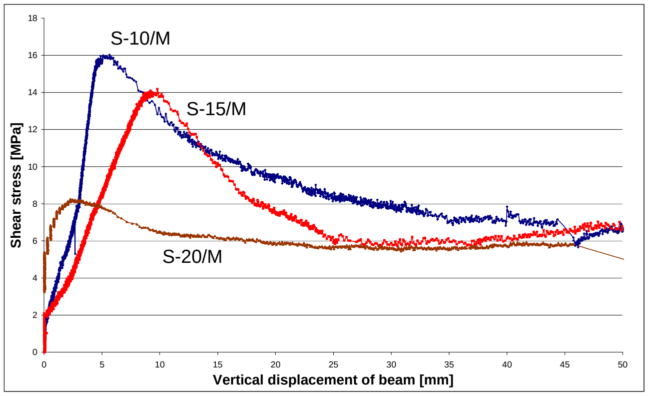


Figure 6: Shear Capacity of Coupling Beams with Different Span-to-Depth Ratio

Most of the current concrete standards disregard the influence of span-to-depth ratios on the overall performance of an element in shear introducing a concept of a critical section instead. However, it is evident that there is a relation – especially prominent in case of deep beams.

Figure 7 shows the experimental shear strengths and predictions by the British code BS 8110 and European code EC 2 for the specimens with different span-to-depth ratios. It is seen from Figure 7 that the shear strengths predicted by the two codes are only about 30% to 60% of the test strengths. The present concrete codes of practice underestimate significantly the actual shear strengths of the SFRC coupling beams.

In Table 2, a comparison is made for Specimen S-20M (Span-to-depth ratio = 2.2) between the test results and the predictions by the codes of practice, where the contributions of the materials including concrete, steel, and fibre (Ashour et al. 1992) to the shear resistance are also presented. It is seen that the contribution of the metal fibre to the shear resistance of the specimen is about 30%.

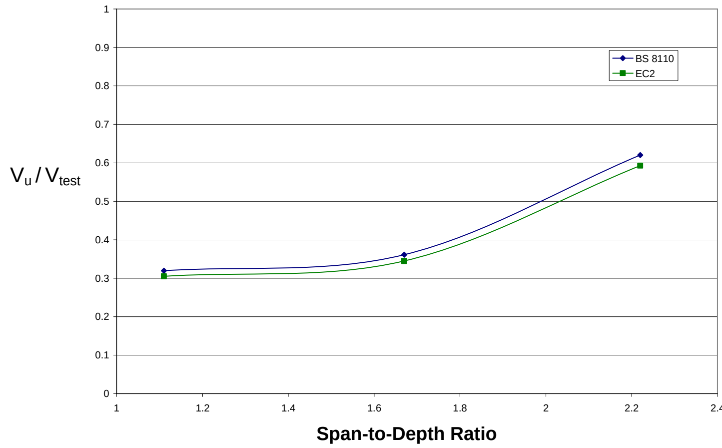


Figure 7: Shear Strengths versus Different Span-to-Depth Ratios

Table 2: Comparison between Test Results and Predictions by Design Codes for S-20M

Design code	Concrete (kN)	Stirrup (kN)	Fibre (kN)	Total (kN)	V_u / V_{test}
BS 8110	38.1	89.3	56.7	184.2	0.62
EC 2	35.1	84.2	56.7	176.0	0.59

DISCUSSION

The calculations of shear strength for concrete beams in BS 8110 and EC 2 are basically based on a simple truss analogy. For greater accuracy of the predictions, empirical constants have been added based on statistical analysis of large numbers of simply supported beam tests. This solution ensures a large safety margin, but it is so at a high price.

Now compare the failure modes of coupling beams and simply supported beams from the point of view of fracture mechanics. It is quite reasonable to assume that cracking of concrete elements will appear alongside the principal compressive stresses. For simply supported beams, the principal compressive stresses create an arching action between the supports with longitudinal reinforcement being the tension tie. In this case, shear cracks are generally initiated from flexural cracks from the bottom surface of the beam to the longitudinal reinforcement and then proceed alongside the compressive arch. The crack mouth is formed on the underside of the beam and the crack progresses upwards. This process has been presented in a simplified linear elastic fracture mechanics model (Jenq and Shah 1989).

However, for coupling beams the situation is quite different from for simply supported beams. The diagonal shear cracks are initiated on the inside of the beam and progress in both directions as shown in Figure 8 at four stages of development. The beam increases its load all the way until the major crack reaches both sides of the beam as shown on the last figure of Figure 8.

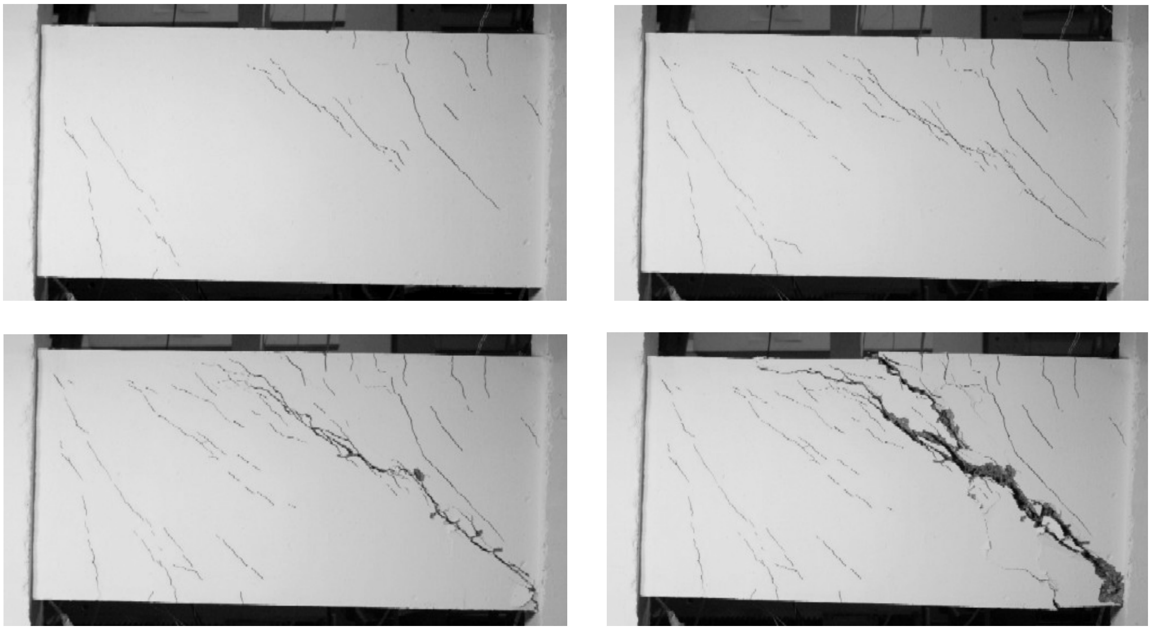


Figure 8: Crack patterns of coupling beams

It is therefore justified to say that the design of coupling beams should be treated to be different from the design of simply supported beams. Simple provisions for design of coupling beams should be prepared for engineers, especially for deeper coupling beams as they tend to be neglected in concrete standards.

Since the traditional reinforced coupling beams cannot generally meet the shear strength requirements, composite solutions have been introduced instead. A comparison is here presented between the steel fibre reinforced concrete beams and the reinforced concrete-encased steel plate composite beams (Kuang and Cheng 2004). The results are presented in Figure 9.

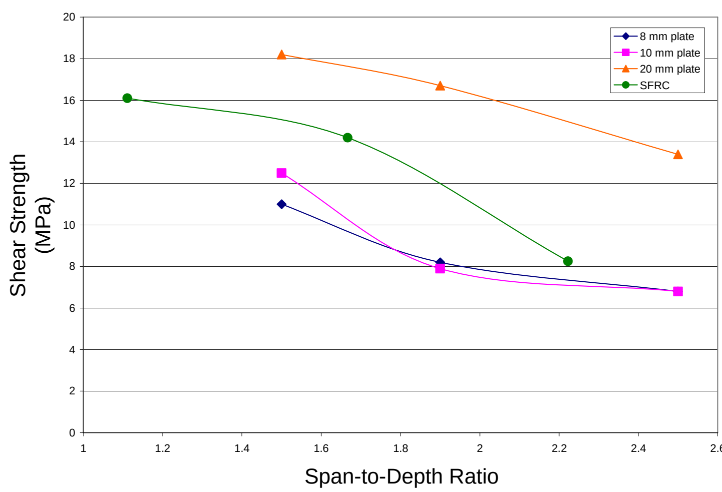


Figure 9: Comparison between SFRC and composite coupling beams

As the composite solution doesn't use transverse shear reinforcement in the beams, the shear resistance relies entirely on the contributions of the steel plate and concrete. For the steel fibre solution, both fibres and transverse reinforcement are used to resist shear.

It is believed that the use of steel fibre concrete can be used instead the steel plates as almost equally strong, but cheaper and much less troublesome in construction difficulties.

CONCLUSIONS

Large scale steel fibre reinforced concrete coupling beams are tested. Based on this experimental study and comparison of test results with those predicted by codes of practice, the following conclusions are drawn.

- A new system for testing coupling beams has been developed. The system can be used for both monotonic and reversed cyclic load tests of coupling beams. The system can also be applied to specimens with different span-to-depth ratios without the necessity of changing the beam's depth which allows for easy comparison between specimens of different geometries without resorting to unclear issues of size effect.
- The tests show that adding even small amounts of steel fibres into concrete can substantially improve the shear behaviour of concrete elements. Steel fibre is shown to have very significant effect on the enhancement of shear strength of traditional concrete. The SFRC coupling beams exhibit much higher shear capacity than that of conventional reinforced concrete ones. The best scenario in this investigation is that the shear strength is 3 times the design strength predicted by the codes of practice.
- The use of steel fibres together with shear reinforcement in conventional RC coupling beams can provide shear capacities close to those of RC-encased steel plate composite coupling beams.
- It is suggested that the design of coupling beams should be performed on a different basis than simply supported beams as their structural behaviours are very different.

REFERENCES

Ashour, S.A., Hasanain, G.S., and Wafa, F.F. (1992). "Shear Behaviour of High Strength Fiber Reinforced Concrete Beams." *ACI Structural Journal*, 89 (2) 176-184.

Batson, G., Jenkins, E., and Spatney, R. (1972). "Steel Fibers as Shear Reinforcement in Beams." *ACI Journal*, 640-644.

Casanova, P., Rossi, P., and Schaller, I. (1994). "Can Steel Fibers Replace Transverse Reinforcements in Reinforced Concrete Beams?" *ACI Materials Journal*, 94 (5) 341-354.

Irwin, A.W. (editor) (1984). *Design of Shear Wall Buildings*. CIRIA, London, UK.

Jenq, Y.S., and Shah, S.P. (1989). "Shear Resistance of Reinforced Concrete Beams – A Fracture Mechanics Approach." *ACI Special Publication*, SP 118-11, 237-257.

Kuang, J.S., and Cheng, P.C. (2004). *Shear Strength of Reinforced Concrete-Encased Steel Plate Composite Coupling Beams*. Research Report, Dept. of Civil Engrg., Hong Kong Univ. of Science and Technology, Hong Kong.

Lim, T.Y., Paramasivam, P., and Lee S.L. (1987). "Shear and Moment Capacity of Reinforced Steel-Fibre-Concrete Beams." *Magazine of Concrete Research*, 39 (140) 341-354.

Paulay, T. (1969). *The Coupling of Shear Walls.* Ph.D. Thesis, Dept. of Civil Engrg., Univ. of Canterbury, Christchurch, New Zealand.

Subedi, N.K. (1989). "Reinforced Concrete Beams with Plate Reinforcement for Shear." Proceedings of Institution of Civil Engineers, Part 1, *Design and Construction*, 87 377-399.