The Author. *Fig. 4*, as suggested by Mr. Cartwright Reid, and he thought they were quite correct. Some explanation of the method upon which the calculations had been made seemed desirable. In order to determine the tensile stress in the concrete at failure, that was at the load at which cracks were observed, it was necessary to assume the whole of the concrete to be capable of resisting tension, but allowance was made for the area of the transverse elevation of the stirrup on the tension side of the neutral axis, since it was thought that that area was not effective for resisting tension. It was further assumed that the modular ratio of steel to concrete was 12.

The Author concluded his remarks by showing several lantern-slides illustrating reinforced-concrete vessels.

Correspondence.

Mr. Binnie. Mr. W. J. E. BINNIE wished to place on record the results of a few tests made to determine the effect of adding a waterproofing compound to concrete and neat cement mortar.

Cross Breaking Strength.—Beams 15 days old and 20 inches by 2 inches (deep) by 1 inch were broken, over a span of 18 inches, under a steadily applied central load. The percentages stated below were in terms of the weight of cement, and the stresses were the moduli of rupture. Three beams of each class were broken.

3 : 2 : 1 MIXTURE WITH GRAVEL AGGREGATE PASSING ¼-INCH RING.

Proportion of Waterproofing Compound ("C").	Stress.
5 per cent.	431 lbs. per sq. in.
3 ,, ,,	401 ,, ,,
Nil	403 ,, ,,

NEAT CEMENT.

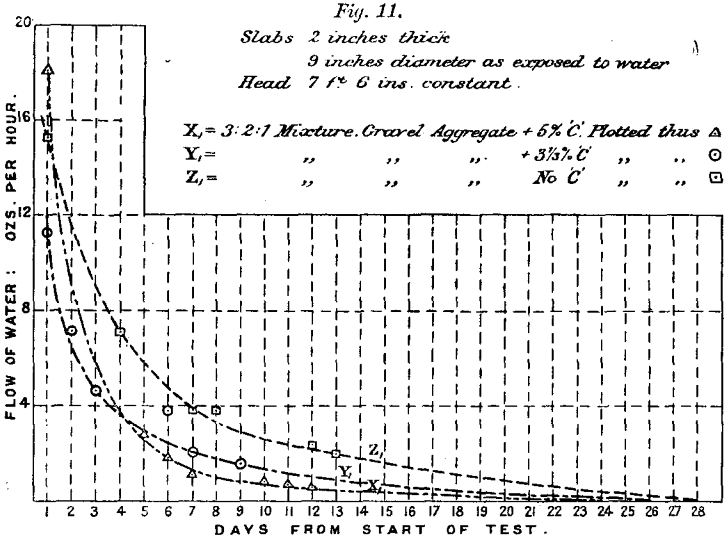
5 per cent.	820 lbs. per sq. in.
3·75 per cent.	641 ,, ,,
Nil	726 ,, ,,

Absorption.—Three 6-inch cubes of 3 : 2 : 1 mixture with gravel aggregate were made, one of each kind. These were tested for absorption after 14 days. The percentage of water absorbed was stated as compared with the weight of the dry cube. The percentage waterproofing compound was in terms of the weight of cement. Mr. Binnie.

Proportion of Waterproofing Compound ("C").	Absorption
5·4 per cent.	2·3 per cent.
3·6 ,, ,, ...	1·7 ,, ,,
Nil	5·2 ,, ,,

Permeability.—Three disks 2 inches thick were fitted in the socket end of 9-inch stoneware pipes, and subjected to a pressure of 7 feet

Fig. 11.



6 inches of water after the disks were 21 days old. *Fig. 11* showed the falling-off in the rate of percolation during 14 days. The lowest rate was equivalent to 0·15 gallon per square foot per 24 hours. After being subjected to water-pressure for one month, all the disks showed no signs of moisture on the under side.

Mr. G. Woulfe Brenan considered that the Paper was valuable to all interested in concrete work, whether for sea or land. He agreed with the Author's remarks as to the better crushing results from a concrete made with an aggregate of small round particles than with angular chips for reinforced-concrete work, and for the reason given by the Author. The mortar had more ready access amongst globular forms, and there was less chance of voids through the chips being blocked by themselves and by the bars, stirrups, and the wires. Within the small thickness of 2 inches, blocking was likely to occur, and therefore the aggregate for such particular work Mr Brenan.

Mr. Brenan. ought to be as mobile as possible. With regard to the Table showing the position of the bars 1 to 5 in the cross section of the sample beams (*Fig 2*), it seemed that in all of them, except No. 5, the cover was only $\frac{1}{4}$ inch thick. That was practically no cover, and this would certainly induce cracks on the tension side. He had never seen crushed granite washed when used for an aggregate. It would be an unwarranted expense in practice, but he knew that granite, when crushed and used both as aggregate and sand, gave the best possible results, both as to strength and rapidity of setting. It had been used in repairing concrete piles damaged on face and arris, and within $\frac{1}{2}$ hour after the repair was finished—protected, of course—it was exposed to lapping waves, and the result was entirely satisfactory. He thought that the fendering of concrete ships should be of wood rather than concrete. The position of fenders was always exposed to sea wash. He had noticed that concrete pavements on the sea front, and the face of concrete parapets on piers and breakwaters, had a strong tendency to disintegrate after 8 or 10 years' exposure. The surface was pitted through small stones coming out, while the joints opened through shrinking of the mass on each side, and cracks appeared. He believed it would be necessary to use preservative solutions to seal up the front sides of the ship more than the insides.

Mr. Fowling. Mr. C. Fowling observed that the Paper contained much useful information, and it was very desirable that the knowledge gained of late, as to the use of reinforced concrete in ship-construction, should be collected and recorded for future reference. The building of reinforced-concrete vessels during recent years had been a war emergency measure, brought about by shortage of ships, and by deficiency of the ship steel necessary for their replacement. Reinforced concrete had proved itself eminently satisfactory in large land structures, and it had been used to a limited extent for pontoons and barges and a few small floating craft whose service was restricted within narrow limits. It was considered that the material might be found adaptable for vessels of moderate dimensions, and that, so far as this country was concerned, such vessels might be very useful for coasting and cross-Channel work, for which type there was a great demand. There was practically no information obtainable as to the reliability of reinforced concrete for the construction of ships, in which the stresses to be withstood varied so greatly from those in buildings on land. The Admiralty took the lead in this country and ordered a large number of barges and several tugs to be built, and these orders were placed with firms

Mr. Fowling.

scattered around the coast, most of whom had had no experience in the construction of ships. Norway had then already begun to build small vessels, and the United States later on commenced reinforced-concrete construction with a steamer 320 feet long, the S.S. "Faith," which was still running and had made a voyage to this country. Most of the continental countries had also begun to make investigations as to the practicability of using reinforced concrete for small vessels, and when designs and plans for the construction of such vessels were received by Lloyd's Register, it became necessary to adopt a basis upon which these proposals could be uniformly dealt with. In dealing with the plans, it was necessary to consider the proposed arrangement of longitudinal, transverse and slab reinforcement in detail, together with the sizes of all concrete members, also to make detailed calculations of the bending moments on all transverse and longitudinal members, and calculations showing the tensile and compressive stresses and the shear on the various members of the sections, in addition to the stresses and shear on the vessel itself due to longitudinal bending.

The maximum tensile stress permitted in the main structural reinforcement, which was of steel, was about $6\frac{1}{2}$ tons per square inch; for bulkheads and local strengthening a higher stress was allowed. No value was given to the concrete for tension. The maximum stress permitted on concrete under compression was 650 lbs. per square inch, with a maximum shear stress of 70 lbs. per square inch. In dealing with the longitudinal strength of the structure, the vessel was considered as supported on the crest of a wave in a light and in a loaded condition, also in the trough of a wave of standard dimensions, namely, equal in length to the vessel and of a height equal to $\frac{1}{20}$ the length. The hydrostatic pressure on the principal members, such as shelling and framing, was taken as that due to the deck level, and the load on the deck was assumed to be equivalent to 5 feet of homogeneous cargo evenly distributed and estimated at 50 cubic feet to the ton.

To ensure, as far as practicable, the use of suitable concrete, crushing and permeability tests were required to be made in all cases before the vessel was commenced. The cement used had to comply in every respect with the British Standard specification for Portland cement of the "slow-setting" variety. The sand had to be clean and sharp, and the maximum size of the larger aggregate was required to pass through a $\frac{3}{8}$-inch square mesh screen. Aggregate as well as sand was required to be free from clay and all animal or vegetable matter. The proportions adopted ranged from $1 : 1\frac{1}{2} : 1\frac{1}{2}$

Mr. Fowling. to 1 : 1 : 2 and 1 : 1·2 : 2·44 for cement, sand, and aggregate respectively. To ascertain the general suitability of the proposed concrete for the purpose of ship construction, the following crushing-tests were imposed :—

(1.) Six 4-inch cubes were required to be made as soon as the constituent materials had been delivered and the proportions determined. The cubes to be seasoned in the builders' cement store for 2 days in air, then 2 days in water at a temperature of between 50° and 60° F. They were then carefully packed and forwarded to an approved testing laboratory. Three of the cubes were tested when 7 days old and the remaining three when 28 days old.

(2.) Six cubes were made during the construction of each vessel from the concrete actually being used, taken directly from the mixer. These were seasoned and tested similarly to those first taken, three tested after 7 days and three after 28 days.

These latter tests were intended to give evidence that the concrete being used was consistent with that originally approved. The concrete was required to attain an average crushing strength of 1,600 lbs. per square inch at the end of the 7 days, and 3,200 lbs. per square inch at the end of the 28 days. Although these tests were not very severe, and it was found that they could generally be complied with, yet in not a few instances the material failed to come up to the required standard; on the other hand, in a number of cases the results were exceptionally good, as much as 4,000 lbs. and 7,000 lbs. pressure per square inch being withstood at 7 and 28 days respectively. Wherever it was found necessary to make changes in the quality of any of the constituents of the concrete during the building of the vessel, fresh crushing-tests were required to be made from the new mixture.

For the purpose of testing the permeability of the concrete, three slabs were made at the same time as the cubes for the original crushing-test. These slabs were 9 inches square and 2 inches thick, cast on edge between wooden moulds. No trowelling or surface treatment of the test-slabs was permitted. Three days after casting these were taken from the mould and carefully packed in wet sawdust and forwarded to the testing laboratory. The slabs were then seasoned in water until 24 hours before testing. During these 24 hours the slabs were allowed to dry in air. Fourteen days after casting, each slab was placed under a water-pressure of 30 lbs. per square inch over a circular area 5 inches in diameter for 4 days, at the end of which time the exposed surface should show no signs of dampness. If signs of dampness were present and it was considered that these would dry off, a further 2 days were allowed under the same pressure, after which the exposed surface was required to be dry. After testing, the slabs were broken and their condition was noted. The requirements as to these permeability tests were determined upon after a series of experimental tests had been carried out, at the instance of Lloyd's Register, at the testing establishment of Messrs. David Kirkaldy & Son. In some cases it was found that the concrete which gave the best crushing results failed to meet the requirements as to percolation, while in other cases slabs which gave excellent results in the permeability tests failed under moderate pressures in the crushing-tests. It was considered preferable to depend upon the concrete itself for impermeability, rather than on any waterproof coatings, which might be easily destroyed by abrasion caused by rubbing against wharves or other vessels. So long as reinforced-concrete vessels kept at sea, they appeared to perform their work satisfactorily, but they would not stand the knocking about in harbour or the grounding that a steel vessel would. They had a tendency to develop cracks which might or might not be of importance, but which required careful watching and attention. These cracks might be either contraction cracks, due to the seasoning and contracting of the material, or construction cracks brought about by imperfect joining of the concrete when it was not laid continuously; or they might be stress cracks caused by the stresses, either structural or local, that the hull of the vessel might be subjected to. The concrete vessels were heavily handicapped by their weight, and it had been found very difficult to reduce the weight of the concrete without introducing porosity. It was also generally accepted that for tension, compression and shear, a rich heavy concrete was the best. Mr. Fowling.

The proportion of dead weight to displacement in reinforced-concrete vessels might be taken as ranging approximately from about 50 to 60 per cent., varying with the size of the ship, while in wood vessels it might be 60 to 65 per cent., and in steel vessels 70 to 75 per cent. While reinforced-concrete vessels were at such a disadvantage in the matter of weight of hull, it was not at all likely that their construction would be proceeded with unless it were in times of emergency, such as those through which the country had recently passed.

Dr. Laws. Dr. B. C. Laws remarked that the Paper was probably the most comprehensive dissertation which had yet appeared on the subject. When, early in 1916, the idea of building sea-going reinforced-concrete ships began to take shape, many designs of various types were put forward for consideration with a view to classification. In many cases the proposals had to be rejected as unsuitable for the purposes contemplated. In the initial stages it was evident that the proposers had not realized the distinctive requirements of reinforced concrete used in land structures—subject to static forces, and in sea-going vessels—subject for the most part to dynamic forces. The scarcity of knowledge on the subject was without doubt the cause, at least in part, of the slow development of the work, and compelled much discussion and the carrying out of many experiments before the new system of construction could be accepted. For this reason the Paper, being a record of experiments carried out by the Ministry, should be welcome to The Institution.

The building entered upon could hardly be said to have resulted in any measure of success. Fifteen yards were started in this country for the building of reinforced-concrete vessels, and about sixty vessels of various types, including launches, dumb barges, self-propelled coasting vessels, and tugs had been actually built and had seen service. In America, as well as on the Continent, similar programmes were engaged in. At the present time about fifty vessels altogether were classed with Lloyd's Register. Whether such vessels were a paying commercial undertaking was a question which perhaps could only be answered by the owners themselves. Whether they had really met the demand for which they were conceived was doubtful. The work had progressed slowly, due chiefly to the inexperience of those actively employed in the construction, and few vessels were completed within a reasonable period of the time thought to be sufficient for their construction.

In executing the design and work in such a complex structure as a ship, close co-operation between the concrete expert and the naval architect or shipbuilder became necessary.

For ships the naval architect required a material which was strong, elastic, and homogeneous in character, and in steel he could secure all these properties, to a degree more or less uniform, wherever and by whom the steel might be made. Concrete, on the other hand, could not be depended upon for all these necessary attributes, and practically speaking it was entirely wanting in elasticity. The grading of the aggregate, the process of mixing to the required proportion and consistency, and the placing and tamping in position, depended so much on the personal equation of the worker that uniformity, which was so desirable a quality in shipbuilding, could hardly be hoped for. The resistance of concrete to crushing was such that if a sufficiently large bulk of the material could be employed, as in land work, concrete would be very useful as an element of construction. But in ship construction, the quantity of concrete used had to be reduced to a minimum, and although concrete had some resistance to tension, it was relatively so small that in ship designing it might be neglected. Dr. Laws.

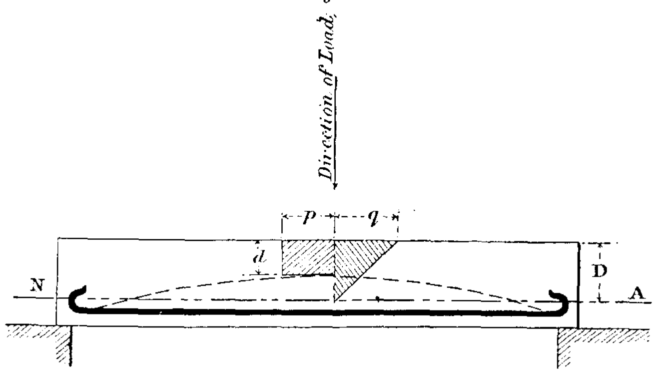
The great bulk of the concrete used was contained in the deck and shell slabs, and the minimum thickness which might be accepted for these portions of the structure had from time to time formed the subject of discussion with a view to economy. There were reasons, both theoretical and practical, which precluded the reduction in thickness of the slabs below a certain amount. From a theoretical standpoint the reasons might be summed up in the fact that the slabs had to house the main structural reinforcement, and at the same time the latter had to be so situated as to give to the slab itself the necessary strength for local work, such as withstanding hydrostatic pressure. Again, ships were liable to be roughly handled in the process of wharfing and docking, or damaged by grounding; and thin slabs stood a very good chance of being fractured or cracked; indeed, serious damage might result from blows which would hardly affect ordinary steel vessels beyond perhaps the indentation of a plate, or the slight bending of a frame. No amount of protection, such as that afforded by wood rubbing-pieces and fenders would entirely obviate the liability to fracture from these causes, and apart from this, experience had amply proved that the concrete, specially in the deck slab, became cracked more or less, due to structural straining. The fact that the concrete did crack under the action of the usual forces to which a ship was subject, and was liable to be seriously fractured or broken as the result of impulsive blows, as in the case of collision or wharfing, tended to render the material unsuitable —at least at present—for the construction of ships. Serious fracture of the concrete might entail the loss of the vessel, and in all cases of cracking or fracture there was a possibility of damage to cargo.

On p. 229 figures were given for the crushing strengths obtained from concrete cubes—ranging from 1,450 lbs. to 4,750 lbs. per square inch at 7 days, and from 3,000 lbs. to 7,000 lbs. per square inch at 28 days—and the Author went on to say that "this variation in strength was considerable; but a percentage variation of equal

Dr. Laws. amount in the elastic limit of steel used in ship construction is not unknown." The Author's meaning here was not quite clear. Mild steel, as generally used in the construction of a ship, had fixed limits of 26 and 33 tons per square inch—depending upon the part of the structure to which the steel was assigned. Further, the steel was required to have a certain percentage elongation in a definite length. The margin indicated is recognized as being the maximum, and the stretch per cent. the minimum, allowable in order that the necessary ductility and elasticity might be assured, and to guard against brittleness. Except for a small range outside these limits, the material was rejected if, on test, the conditions were not fulfilled. Taking the lower limit as the basis, the variation for steel was 27 per cent.; this in no way corresponded with the variation in crushing-stress of the concrete quoted by the Author. Further, the question arose whether concrete of the usual proportions, represented by the higher figures, namely, 4,750 lbs. for 7 days and 7,000 lbs. for 28 days, would not, through rapid maturity, be more easily fractured under impact, in the same way that mild steel might be expected to be damaged had the higher limits specified been overreached. But apart from this it was well known that so far it has not been found possible to obtain that uniformity which was so desirable in a material to be used for the purpose of ship construction. Tests on cubes made from concrete taken from the mixer had not agreed with similar tests made on material cut from the vessel, apart altogether from the question of age; and further, tests made on materials cut from different parts of the vessel had not been found to agree uniformly between themselves.

It was noteworthy in bending-tests illustrated in *Figs. 1* and *2*, where the reinforcement was anchored, and where precautions had been taken that the reinforcement was sufficient to enable ultimate failure of the beam to take place by crushing the concrete, that the *estimated* crushing-stress of the concrete was greater than that shown in cubes of the same material when subject to pressure. Experiments such as the one referred to had generally been made on beams of comparatively short span, and the results obtained often gave rise to the impression that the crushing strength of the concrete had been increased in some mysterious way by the presence of the reinforcement. The estimated value of the crushing stress was unreal, and an explanation might be found, in that after the reinforcement had been so stressed that the concrete below the neutral axis had actually given way under tension, the concrete in that portion of the beam above the neutral axis assumed the form of an arch with abutments at the anchorage or hooked ends of the reinforcement; the section of the arch being subject to a more or less uniform crushing-stress. On this assumption the depth, d, of the arch would be something a little greater than half the depth D of the neutral axis from the upper face of the beam (*Fig. 12*). Dr. Laws.

Fig. 12.



NA denotes the initial position of the neutral axis of the beam. If p denotes the cube-test value and q is the estimated value for crushing,

then $$p \times d = q \times \frac{D}{2}$$

or $$q = \frac{2 \times p \times d}{D} \quad (> p \text{ by hyp.}).$$

i.e., the depth d of the arch (concrete under compression) at the apex is a little greater than half the distance of the neutral axis from the upper face of the beam.

In test beams of considerable length one would not expect such a result as that given by the Author for short beams. The concrete in compression would be free to follow the ordinary law of variation between the neutral axis and the extreme lamina of the concrete beam—which was what probably took place in practice.

Reference was made by the Author to the use of shell discard steel. It might not be out of place to emphasize the fact that the use of such steel had been permitted only in non-structural parts of the vessel, such for example as deckhouses, screen bulkheads, and the like. Steel of a reliable character and of a higher tensile value than mild steel had been permitted in certain parts of the structure other than the main structural members. In such cases no reduction in sectional area of the material had been allowed; for although in such instances a greater elastic limit was obtainable in the steel, the modulus of elasticity upon which the stress calculations were based remained practically the same as in mild steel.

Dr. Laws. The question of the precise condition under which the bond stress might be destroyed was probably a very open one. The Author stated that the elastic limit of the steel *determined* the condition, and beyond this the bond failed. It would add to the value of the Paper if the Author could give any reasons, either theoretical or experimental, from his own experience, supporting this view, and show to what extent they might agree with the ordinary formula $f = \frac{S}{a}P$ for the value of the bond stress. The experiments illustrated by *Fig. 5* were interesting, and the load-strain diagrams were instructive. It was presumed that the view expressed in the Paper was "that the failure of the concrete in tension is gradual," it would seem that the point in the diagram at which the graph took two decided directions corresponded either to the *sudden* failure of the concrete to resist tension, or the bond stress broke down, or possibly a combination of both, in which case the reinforcement, being suddenly subjected to an additional stress, would pull out, with the result indicated in the Figure.

It was impossible to foresee what the future might have in store for the success of reinforced concrete in the building of ships. Some of the vessels had proved themselves better than others on service, and doubtless some of the gentlemen interested in the building of these vessels would be able to give The Institution the reasons for their success. But, on the whole, it would seem that until a concrete could be produced which could be depended upon for uniformity, and which possessed the property of elasticity, the material was not likely to prove a successful competitor with steel in the building of vessels for sea-going purposes.

Mr. McNeill. Mr. C. S. McNeill remarked that the Paper was a very instructive one, especially to harbour engineers, and the experiments were valuable, though, as the Author stated, they were not sufficiently extensive to enable general conclusions to be drawn. In concrete made with rounded beach gravel the Author appeared to have obtained better crushing results than with an aggregate of broken stone. In the experiments made to test the tensile strength of concrete, however, the relative values of the different aggregates were not distinctly shown. Mr. McNeill was of opinion that concrete of a hard, non-porous broken stone, mixed with sand, should give better tensile results than one of rounded beach gravel, mainly on account of the better adhesion of the cement to the rough aggregate, but he would like to have more information on this point. Provided such a concrete was properly tamped when placed within the moulds, there should be little liability of its catching on the reinforcement and creating voids, etc. Mr. McNeill.

The deflection diagrams (*Figs. 5* and *7*) were useful, as indicating the points at which the concrete ceased to resist tension, and proved that the resistance of the concrete in tension added appreciably to the rigidity of the beams; but the uncertainty of concrete work rendered it doubtful whether this tensile strength could be relied upon to any appreciable extent. In the test beams shown, the percentage of the reinforcement was very high and uneconomical, and it was not clear why so much steel was employed. Judging from the upper portions of the curves (1) *Fig. 5*, and those in *Fig. 7*, it would appear that the elastic modulus of the concrete would be approximately equal to 2,000,000 lbs. per square inch, thus making the modular ratio of steel and concrete 15, where the tensile strength of the concrete was neglected. He desired to know why the value 12 was adopted in preference to 15, the value generally used in this country.

The results of the tests on watertightness were very satisfactory, and indicated that, so long as the concrete had been carefully made and moulded, a thinner covering than that usually given to the reinforcement would prove satisfactory. In harbour practice recently the tendency had been to increase the thickness of the covering, and to have at least 2 inches of concrete over the steel. Several years ago he constructed several columns in reinforced concrete to support a shelter in which only a $\frac{1}{2}$-inch of covering could be given to the reinforcement. Although these columns had been exposed to sea spray and moist atmosphere they had remained quite sound.

Mr. J. Turner Morris, referring to the 28-day crushing test results given on p. 229, which showed the strength of the concrete that certain builders proposed to use, the results obtained for each vessel at a later stage showed, in most cases, a lower value, due to somewhat poorer cement and less exact grading of the sand and aggregates as the supplies became exhausted. Several 28-day crushing test results dropped to 2,000–2,500 lbs. per square inch, and the classification societies had to keep the standard up to 3,200 lbs. per square inch before the concreting could be continued. Before further building of reinforced-concrete vessels took place, it would be advisable for builders to convince Lloyd's Register of the safety of removing the notation "Experimental, subject to annual survey," and to give the vessels a full unrestricted class. Further, the designs could be made lighter by closer intercourse between designers and the classification societies, on whom the responsibility Mr. Morris.

Mr. Morris. for the weight and structural strength of the vessels lay in practice. This latter point referred most particularly to foreign owners.

It would appear to be advisable to coat the outside of the bottoms of vessels which had been cast on a concrete dock-bottom, and to have greased paper to prevent the slab bottoms of the vessels from remaining stuck to the dock. This paper in practice formed into rolls as concreting took place (only being discovered later when the vessels were in dry dock), and in places reduced the thickness of concrete cover at the underside of the bottom slab.

The increased cost of twisted bars with the triangular section over the plain round rods was a useless expense, as no higher stress was allowed by Lloyd's Register.

Mr. Williamson. Mr. JAMES WILLIAMSON considered it doubtful whether the weight of a concrete hull made with the class of concrete used in the concrete vessels of the Ministry of Shipping would be increased by anything approaching 2 per cent. due to absorbed water. The 9-inch by 9-inch by 2-inch concrete slabs prepared from the concrete as used in the ships at the Shoreham shipyard were, in many cases, weighed before and after subjection to the percolation test. The slabs were generally 14 days old at commencement of the test, and the water-pressure, equal to a head of 69 feet, was applied for 4 days on one side of the slab. In the worst case, for a set of three slabs which showed a deficient percolation result and a rather low crushing test, the increase in weight was less than 2 per cent. Normally the increase was very small and was sometimes nil or even slightly negative. For a hull made with this class of concrete and subject to less than 20 feet head on a portion of the surface only, the amount of water absorbed would probably be very small. In one set of three percolation tests made with concrete weighing less than 90 lbs. per cubic foot, the extraordinary result was obtained that the slabs were 1·8 per cent. lighter after the test than before.

In designing reinforced-concrete tanks to hold water, which might be considered as to some extent the converse of the concrete ship problem, it was common practice on the Continent, if not in this country, to limit the stress on portions subject to tension to an amount which would ensure that the rupture stress of the concrete in tension would not be exceeded. This precaution was taken with the object of avoiding cracks, and generally meant that the steel, if assumed to take the whole of the tension, required to be stressed at less than the usual 16,000 lbs. per square inch.

The Author seemed to contemplate the whole length of a bar contracting in diameter, when the stress exceeded the elastic limit, and the adhesion consequently being destroyed. In any actual case there would usually be a limited region of maximum stress on a bar which would determine the place where abnormal extension with contraction of area first took place, and, as was the case in testing a piece of mild steel, the serious contraction would be localized here. It was very doubtful if adhesion of a bar in reinforced concrete was ever destroyed other than locally in this manner by contraction of the steel at stresses beyond the elastic limit. He was inclined to think that a somewhat contrary effect sometimes occurred. It was well known in connection with testing mild steel, that if the length in which extension and contraction could take place was artificially restricted, the ultimate test strength of the piece would be increased. In certain bending tests made on slabs reinforced with thin rods, the slabs broke by failure of the steel in tension at calculated stresses higher than the actual ultimate test strength of the bars. There appeared to be no loss of adhesion other than locally at the fracture, and, if it happened that the grip conditions of the concrete determined that the extension of the bar was confined to an unusually restricted length, the result would be accounted for. Admittedly the calculations were widely approximate for conditions beyond the elastic limit, but it would be interesting to know if the effect had been observed elsewhere. Mr. Williamson.

The modular ratio was very commonly assumed at 15 for all kinds of concrete, and the same for both tension and compression, although accurate results as to the tension modulus were scanty. The London County Council Regulations called for a diminishing ratio with increase of richness of the concrete, which was in the right direction. The actual modular ratio for the beach gravel concrete used at Shoreham, average proportions 1 : 1 : 2, was about 9 in compression within the range of working-stresses. It was clear that the assumption of a ratio of 15 might lead to very erroneous results in calculation if the actual ratio were 9. If, for example, in the case given on p. 234, the ratio were taken as 9 instead of 12, the result in tension on the concrete would be about 360 lbs. per square inch, instead of 325 lbs., but calculations of this nature must necessarily be interpreted with a very wide margin of uncertainty. Heavy rich concrete with such a low ratio had the great disadvantage that the use of steel as compression reinforcement, unavoidable in ship construction, became very uneconomical unless the concrete could at the same time be very highly stressed. The lower the modular ratio also, the sooner might cracks be expected to develop on the tension side of members. The Author suggested (p. 234) the desirability of having a reinforcing material with a

Mr. Williamson. higher modulus of elasticity than steel. There would be much more hope of manipulating the concrete element of the combination, so as to make this have a lower actual modulus, thus attaining a higher modular ratio, and this would equally well effect the desired result. A concrete giving a modular ratio of 25 to 30 would be a very useful material from this point of view, and if this could be attained along with a large reduction of the weight of the concrete, the field for the use of reinforced concrete in large structures would be widely extended. Investigations towards attaining such a concrete were under way towards the conclusion of the concrete ship programme, using both natural rock and artificial kiln manufactured material as aggregate, and with every prospect of success. Adequate crushing strength could be attained with concretes weighing between 90 and 110 lbs. per cubic foot, and the astonishing percolation test attained with the natural-rock concrete had been already referred to. There was clear evidence that these light concretes gave higher modular ratios than the dense concretes used in the ships, the actual ratio being in the region of 15, which was much better than 9.

The diagram (p. 241) showed that the five rods in each side of the hollow section under test were bent out to an angle of about 19° at the bottom. The bars when under tension would have an outward resultant at the bend equal to about one-third of their stress. In the case of the corner bars this resultant would be adequately resisted by the rectangular links if of suitable number and size. The straight parts of the links on the 14½-inch sides, however, offer inadequate resistance to the outward tendency of the three middle rods on each side, and for this reason the tendency to rupture at this place was largely increased, and allowance must be made for this in interpreting the results. The conclusion drawn from these experiments (p. 243) that "with 2 to 3 tons per square inch stress in the steel, it was almost certain that cracks would be formed in the concrete slabs of ships," was surely not well founded. Actually the steel in skin slabs of many concrete vessels was designed for a working-stress of 16,000 lbs. per square inch, under a head of sea-water up to deck-level. In service conditions the stress on portions of the slabs must certainly be constantly exceeding 2 to 3 tons per square inch (probably up to 6 tons per square inch), and constantly varying up and down though not reversing. If the conclusion were sound, then cracks ought now to be showing on the slabs of vessels in actual service. It was the case, however, that practically no cracks (other than due

Mr. Williamson.

to accident) had been observed to occur on the sides or bottoms of the thirty or forty vessels which had been in service. Indeed the absence of cracks on such large areas of concrete was truly remarkable. On the decks of vessels, however, cracking had been observed in many instances. The decks were pierced with hatches, ventilators, pumps, etc., and these openings facilitated the starting of cracks, and in certain vessels the arrangement of steel reinforcement in the deck had tended to invite cracking. The deck also was much more subject to temperature influences than other parts of the vessels.

The result of experiments with one composition at Shoreham showed a loss of strength in the concrete and a lowered resistance to percolation, as compared with the ordinary concrete without composition. It was his opinion that, even where rich concrete was not required from strength considerations, watertightness would be more satisfactorily and more cheaply obtained by adding extra cement than by adding waterproofing composition. As some of the vessels in service showed rapid fouling and growth of "grass," it was decided to have them coated outside as opportunity offered. Some were coated with "Bitumastic" solution, and others with coal tar. In his opinion distilled coal-tar (from which all the lighter fractions had been driven off) thinned down with naphtha to a consistency permitting easy application with a brush, was a suitable and cheap coating for concrete, whether for marine or acid-resisting purposes.

The Paper made no reference to a matter of shearing strength (closely allied with tensile strength), which had proved one of the most defective features of the concrete vessels in service. There was little question as to the adequacy of the shearing strength of the slabs, as beams resisting water-pressure loads between the frames, and the side webs or skins, which resisted the main structural shearing stresses of the vessel, could be designed with ample strength for the purpose. The matter of punching shear, or resistance of the concrete to moderate or severe local knocks and blows was a different proposition altogether. Neglecting fractional variations, the ratio of tensile, compressive and shearing strength for mild steel might be stated as 1 : 1 : 1. The corresponding ratio for the steel and concrete used in shipbuilding would be about $1 : \frac{1}{20} : \frac{1}{100}$ to $\frac{1}{200}$, the unit 1 representing the strength of the tension steel. The deficiency of the concrete in compression was made up for by additional area of material, remembering that resisting moment of slabs, etc., increased practically as the square of the thickness. But, having made the increase of thickness in respect of compressive strength, there still

Mr. Williamson. remained a relative deficiency of one-fifth to one-tenth, as compared with resistance to punching shear of an equivalent steel plate skin. For example, corresponding thicknesses would be in a particular case $\frac{1}{2}$-inch steel plate and 5-inch concrete ; the concrete was ten times as thick, but its resistance to punching shear was probably only one-fifth to one-tenth of that of the steel plate, and in addition the one material was brittle and the other was ductile. In practice, the effect of a moderate blow on a small area on the outside of a slab was to cause a flake of concrete of somewhat larger area to spall off from the inner layer of reinforcement on the inside, with some cracking through the skin. With heavier blows greater damage was done, until with a certain force a hole, generally small outside and large inside, was punched through. All this might occur with blows which would not seriously damage a steel vessel. In some cases slabs had been holed above water without anyone on board being aware that the vessel had been struck. The proved tenderness of concrete vessels when aground was mainly due to the same cause, though the greater stiffness of the concrete vessel was a further disadvantage.

The Author. The AUTHOR, in reply, referred to Dr. Laws's request for an explanation of the sentence " but a percentage variation of equal amount in the elastic limit of steel used in ship construction is not unknown," used on p. 229, in commenting upon the large variation in " crushing " stresses of the concrete test blocks. On reflection, this phrase would have been better in a footnote. It had reference to the large variations of the elastic limit of steels that did sometimes occur. As was well known, although there might be no appreciable difference in the ultimate tensile strength of several test specimens, there might be a wide variation in the yield-point. Dr. Laws referred, the Author thought, to ultimate strength and percentage elongation after fracture. These elements did not give any indication of the elastic limit or yield-point. The elastic limit was not measured as a rule in the commercial testing of steel.

As to the Author's statement that the failure of the concrete in tension was gradual, of course the observations on which *Fig. 5* was based could not be so accurate, or be made at sufficiently small increments of load, to enable the actual changes which took place under test to be represented in the diagram. It was shown that there were two definite stages (early experimenters showed this), when a gradually increasing load was applied to a girder, (*a*) in which the concrete on the tension side of the girder was intact and operative, (*b*) in which the concrete was fractured down to the neutral axis. He could not conceive that the whole of the concrete on the tension side of the neutral axis could fail suddenly and completely between the two stages. Subsequent to fracture on the tension side, the action of the concrete might be as described by Dr. Laws in *Fig. 12*. The Author.

He agreed with Mr. Williamson that an absorption of water of 2 per cent. of the weight of the dry concrete hull was certainly likely to be a maximum for a well-constructed hull; but he did not think absorption could be judged from a pressure test on a specimen such as Mr. Williamson described. Some of the untreated slabs of Table V were quite dry on one side after a progressive pressure test lasting 14 days, terminating in a pressure of 200 lbs. per square inch. The ultimate absorption would not be greater, it seemed to him, under a high-pressure test than under a low-pressure test.

With regard to the failure of the bond stress with increase in tensile stress in the reinforcement, it was clear that if the contraction of the bar under tension was such that the bar left the surrounding cement the bond stress would be zero. If the stress at which this occurred was less than the elastic-limit stress a *plain straight* bar would pull out so long as the stress was maintained and so long as the bar was not anchored, because the contraction of area would be progressive. This had occurred in testing beams. The elastic limit was the upper limit of such stress. If the elastic-limit stress were maintained and the bar anchored the bar would fail locally.

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25 January, 1921.

JOHN ALEXANDER BRODIE, President,
in the Chair.

The discussion on Professor Abell's Paper, "Reinforced Concrete for Ship-Construction" was continued and concluded.

EXTRA MEETING.

1 February, 1921.

WILLIAM HENRY MAW, LL.D., Vice-President,
in the Chair.

The following lecture was delivered:—

"Bridging in the Field," by Major GERALD LE Q. MARTEL, D.S.O., M.C.

(Copies of this lecture have been printed in pamphlet form.)