Experimental Studies in Reinforced Concrete.

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It was the comfortable assurance of that urbane Roman poet, Horace, that he had built himself a monument more lasting than brass in the intellectual life of mankind. At the time that he was writing these lines the Roman engineers were constructing those concrete aqueducts and domes that have served mankind on the physical side during the time that Horace had been a source of perpetual delight to the students of classical writings. Which product will endure the longer is an open question. One thing is certain, while many persons of exquisite taste may prefer Horace to our modern writers, all well-informed persons conclude that the engineer of today has surpassed the Roman engineer in the quality and use of concrete.

The number of recent failures of reinforced concrete buildings, attended with the loss of life of workmen, does not constitute an argument against the advance of the practice of this new art, but calls attention to the need of correct theory in design and expert supervision in construction. Steel for buildings is made under highly technical methods, and a searching inspection by trained men, whereas concrete for buildings may be formed by ignorant and unskilled workmen, and may be supervised by foremen who are mostly inexperienced in the art of proportioning and mixing the ingredients. Defective material, either of cement, sand or stone, dishonest skimping of cement and poor inspection, incorrect proportioning, and a too early removal of the wooden forms from the floors molded in cold weather, or heavily laden with stored cement and other materials, are sufficient causes to explain these failures. An increasing number of these may be expected as time goes on and untrained men who have learned their business in other lines of construction, take up the work of building reinforced concrete structures. The resulting loss of life will no doubt call attention to the necessity of regulating by proper building laws this new construction, which has spread so rapidly over the country from sea to sea. In 1902, when the first published results of experimentations appeared in this country from the Laboratory for Testing Materials of Purdue University,

one had to go far to observe instances of reinforced concrete. Last summer in Seattle the writer saw no other type of building in process of construction. At Atlantic City in 1902, when the experiments referred to were placed before the American Society for Testing Materials, there was no instance of the use of reinforced concrete in sight. Last summer, at the meeting of the Society, one viewed the stately and beautiful Marlborough-Blenheim hotel entirely constructed of reinforced concrete; the replacement of the steel pier by reinforced concrete piles and girders; and the construction of a new recreation pier of this type of construction. The growth has been truly marvelous. Not only has the extent of its use in bridges and buildings increased, but the variety of its application is extraordinary. In a list of constructions in which it is successfully and economically used may be included: Retaining walls, dams, tanks, conduits, chimneys, arches, culverts, foundations, floors for buildings, railroad girders, highway bridges, pipes, railway ties, piles, stairs and roofs.

At the present time the underlying mechanical principles and the constants of design are fairly well determined, and we wait upon the architects to express the truth of these principles in a beautiful structure. While this type of construction associates itself with the broad and simple wall spaces and low buildings of the Spanish Mission style, with surface ornaments of tiling and Mosaic, it also lends itself to important modern civic buildings. The stateliness of beauty of the Marlborough-Blenheim Hotel at Atlantic City has been mentioned. The Ingalls Building, Cincinnati, and the new Terminal Station at Atlanta, Ga., are other examples.

Without stopping to discuss the properties of waterproofness, fireproofness, durability, etc., or the multitude of topics of interest and importance that crowd one's mind in connection with reinforced concrete, attention will be simply called to the mechanical principles underlying the construction.

Concrete, like stone, is weak in tension, but strong in compression at a ratio of 1 to 10. Consequently when under flexure, as in a beam, the concrete is not used economically; for it breaks on the lower side in tension before the compressional strength is utilized. A beam may be, however, strengthened, or *reinforced*, by the insertion of a steel rod in the lower side of the beam. These rods are usually bent up near the ends of the beam so as to also reinforce the beam against the diagonal tensional stresses that occur at the ends, due to the combination of shear and direct stress.

Before the rod can come into operation during a flexure of the beam, there must be the necessary adhesion between the concrete and the rod to transfer the stress to the rod, and bring the latter into action. This adhesion varies from 300 pounds to 500 pounds per square inch of the surface of the rod, and under favorable conditions is sufficient to develop the strength of the steel in the concrete. The adhesion seems to be more of a mechanical action than chemical, and is due to the entrance of the fine cement into the microscopic pits on the surface of the smooth rods. Many designers use artificially deformed bars, such as corrugated bars and twisted steel bars, to increase this adhesion.

In this way a beam is reinforced so that both the concrete in compression and the steel in tension may be worked to their full value. Any one who has seen a plain concrete beam broken in a testing machine, and then has witnessed a test of a reinforced concrete beam, will be first of all struck by the apparently greatly increased flexibility of the reinforced concrete beam, which deflects ten times as much as the plain beam before showing any visible cracks, and when the load is removed the elasticity of the steel draws the beam back nearly to its original shape. It is probable, however, that this process of bending the reinforced concrete beam early develops very minute flaws in the concrete which are invisible to the naked eye, so that it is not safe to count upon a tensile strength of the concrete in computing the total resisting strength of the beam. Designers compute the resisting moment of the beam as based upon the compressional stresses in the concrete and the tensional stress in the steel alone.

The original tests at Purdue University were arranged to determine:

1. The increased strength added by a given amount of steel inserted in a plain concrete beam.

2. The law connecting the strength of the beam with the amount of steel.

3. The law connecting the strength of the beam with the position of the rods in the beam.

4. The value of gravel in reinforced concrete.

To determine these relations a series of concrete beams was made of first-class materials with rich mortar. In other words, the beams were carefully made with a combination of one part cement to two parts of sand and four parts of broken stone. The concrete was probably superior to that made in the ordinary process of construction. This was proper because the theoretical laws were being verified, and for that purpose it was

necessary to have uniform materials of good quality. The elements of the strength of the materials entering into the beams were determined first of all; namely, the compressive and tensional strength of the concrete, together with the modulus of elasticity of the concrete, both in tension and compression; the adhesion between the cement and the steel; the elastic limit of the steel; a mechanical analysis made of the materials. Since the beams were long in span compared to their height, and, therefore, the shearing stresses were not important, rods of smooth steel were used. Having determined all the elements entering into the strength of the beam, and then the tested strength of the beam itself, it next became necessary to formulate a mechanical analysis of the combination of steel and concrete in flexure, and, with the experience of the tests of the beams in hand, to derive equations for design and calculation. The truth of these equations and the validity of the process of the analysis could then be checked by reference to the tested strength of the beams. These equations were derived and have been used very largely by engineers throughout the country in designing reinforced concrete structures.

Engineers as a rule have found it necessary to review their knowledge of mechanics in dealing with reinforced concrete, not that there is any new principle involved, but the number of factors in the equations of flexure is greater, and an account must be taken of the relative moduli of elasticity of the two materials, steel and concrete. Furthermore, the lack of perfect elasticity of the concrete leads to an assumption of some other than a rectilinear relation between stress and strain.

Again the neutral axis of the cross section must be determined. Its location is not simply fixed by the center of gravity of the cross section, but is controlled by the amount of steel present, the relative moduli of elasticity of the steel and concrete, and by the position of the steel. The writer's equations have followed the usual assumptions of flexure, with the following special assumptions:

1. That the modulus of elasticity of concrete in tension and compression is the same.

2. That there is a parabolic relation between stress and strain in the concrete.

3. That in the earlier stages of the loading of the beam the concrete carries stress in tension, but later, at higher loads, this tensile strength may be disregarded.

The equations are somewhat cumbersome, but have been reduced to

diagrammatic form in the Transactions of The American Railway Engineering and Maintenance of Way Association, Vol. V, 1894, pages 626 and 627. Empirical equations of simple form are presented in The Engineering Review of Purdue University, Vol. I, 1905.

In calculating the strength of the reinforced concrete beam sufficiently approximate results can be obtained by omitting consideration of the tensile stresses in the concrete, and supposing a rectilinear relation between stress and strain. The moment of flexure is then most simply expressed as the total force in the steel multiplied by the distance to the centroid of the compressive stresses. This latter distance is expressed with sufficient accuracy as a fraction of the depth of the beam, this fraction having been determined by experimental measurement on the tested beams.

Care in all cases must be taken to compute the maximum compressive stress arising in the concrete under the conditions of the problem, and also the amount of diagonal tension at the ends of the beams must be computed and provided for by stirrups, or by bending up some of the rods at the ends.

To conclude this brief consideration of reinforced concrete, a conservative estimate would include the following principles:

1. Concrete is durable and fireproof when made of the proper aggregate.

2. The strength of combination of steel and concrete may be calculated with a sufficiently close degree of accuracy.

3. Shapely and beautiful structures may be built of this material. It is particularly adapted for mill buildings because of the absence of vibrations which are induced in the ordinary type of mill buildings by the rapidly revolving machinery.

4. The cost of a properly designed reinforced concrete building, where wooden forms are used to advantage, need not exceed more than 5 or 10 per cent. of the cost of mill buildings of the ordinary type with brick walls and wooden beams of the so-called slow-burning construction, provided that the concrete may be laid as at present by unskilled labor.