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Probabilistic analysis of cracking moment of ferrocement flexural members

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Characteristic cracking moment equations for the design of ferrocement flexural members are proposed. These are derived based on the results of a detailed Monte Carlo simulation (MCS) studies. In simulation, the strengths of cement mortar and reinforcement and, dimensions of reinforcements and ferrocement members are considered as random variables. The preliminary cross-sections considered for MCS are of realistic dimensions and are those of 37 ferrocement flexural members. The probability density functions of ultimate strengths of weld mesh and steel bars, required in MCS, are determined from the uni-axial tension tests on 187 weld mesh bars, 200 specimens of 4 mm diameter and 80 specimens of 6.8 mm diameter steel bars. Two deterministic equations, proposed earlier by the authors, are used in MCS. It is noted that the statistical variations in compressive strength of cement mortar has significant effect on coefficient of variation of cracking moment, and that the cracking moment follows a normal distribution at 5% significance level. A more rational equation is derived for cumulative distribution function of cracking moment and it satisfies the condition that cracking moment can not be negative. A detailed review of literature on strength and behaviour of ferrocement flexural members is included as supplementary material.

Keywords: Ferrocement, First-crack, Flexure, Monte Carlo simulation, Probabilistic analysis

SUPPLEMENTARY MATERIAL

Studies on ferrocement flexural elements

In this supplementary material, a review of literature on strength and behaviour of ferrocement flexural elements is presented. Since most of the research in this direction was carried out before 1990s, the review covers basically that literature. A historical perspective of developments in the field of ferrocement is presented by Naaman[1].

Rao and Gowdar[2] presented experimental and analytical studies on the behaviour of ferrocement elements in flexure. The main variables considered in this study was the percentage of mesh reinforcement (viz. 1%, 2% and 3%). From the test results they studied the effect of percentage mesh on the ultimate bending strength, modulus of elasticity in bending, load-deflection and stress-strain characteristics. By analyzing the test results they concluded that ferrocement can be treated as two-phase material and provision of reinforcement in excess of 2.5% of the cross-sectional area is not economical. Ferrocement was found to have better cracking characteristics compared to reinforced concrete.

Desayi and Jacob[3] conducted tests on ferrocement flexural elements. The main variable considered was the number of mesh layers in the cross-section. From the test results they concluded that ferrocement elements exhibit large ductility at ultimate and its ultimate strength increases with the increase in mesh content.

To study the ultimate strength and cracking behaviour of ferrocement elements in flexure, Logan and Shah[4] tested a total of 60 beams under symmetrical two point loading. For some specimens the reinforcement was lumped on the compression and tension sides while for the others reinforcement was distributed uniformly throughout the cross-section. Authors proposed equations to predict first crack strength, average crack spacing and maximum crackwidth in ferrocement flexural members. They concluded that : (i) the ultimate strength of ferrocement beams can be predicted using procedures similar to those used in the ultimate strength design of conventionally reinforced concrete beams, (ii) increasing the specific surface area of mesh reinforcement results in more number of cracks of smaller width, for a given steel stress, and (iii) the maximum crackwidth is a function of specific surface of the reinforcement and maximum steel stress.

To compute the cracking moment of a ferrocement beam, Rajagopalan and Parameswaran[5], derived an expression based on the assumption of a linear strain variation across the depth and a non-linear stress-space relationship in the tension zone. They also considered the plastification of mortar present in the tension zone. In the computation of ultimate strength of a ferrocement beam, they considered three different conditions at failure. The analytical results were compared with the experimental results of Logan and Shah[4] and satisfactory agreement was obtained.

To establish the influence of the geometry and orientation of the reinforcement on strength in bending, Johnston and Mowat[6] tested 80 ferrocement specimens under symmetrical third point loading. The various parameters considered were type, amount, strength, orientation and spacing of reinforcement, and, strength and density of mortar. From their experiments, the following conclusions about the factors governing flexural strengths were drawn: (i) the strength of mortar is of little importance, (ii) orientation of mesh wires has a marked effect on the strength of the systems reinforced with expanded metal and welded mesh, (iii) steel strength is of minor importance, (iv) for any given steel content, the performance-cost index is maximized by spacing the layers uniformly throughout the total depth of specimen.

An experimental and analytical investigation on ultimate strength, cracking and deflection behaviour of ferrocement flexural elements were carried out by Suryakumar and Sharma[7]. They tested a total of 36 ferrocement specimens reinforced with varying percentage of mesh reinforcement. They attempted to predict the ultimate strength of ferrocement in flexure using the ultimate strength theory used for reinforced concrete members. The yield strength of mesh wire was assumed equal to its ultimate strength. Expressions for first crack stress and extreme fibre stress were also obtained as function of percentage mesh reinforcement assuming that ferrocement section is a homogeneous section. From this study, they concluded that : (i) conventional reinforced concrete theory can be used to predict ultimate moment of resistance, and (ii) the ultimate strength and first crack strength increase linearly with the increase in percentage reinforcement.

Balaguru et al[8] conducted an experimental and analytical investigation to predict the deflection and crackwidths of ferrocement subjected to flexure. The parameters included in the experimental investigation were type and amount of reinforcing mesh wires. They developed a mathematical model to predict the moment-curvature and the load-deflection curve of ferrocement beam for given properties of constituent materials. They found from the experiments that the specific surface of reinforcement does not have as significant effect on cracking behaviour in flexure as in tension. A regression analysis of observed crackwidths showed that the average crackwidth was primarily a function of the strain in the extreme layers of tensile steel. The design equation proposed to predict the average crackwidth as a function of the steel strains in the outermost layer gave useful upper bound values to the experimental results.

The flexural behaviour of ferrocement slabs reinforced with various types of mesh lay-out and supplementary mild steel reinforcement was studied by Abdul Karim and Joseph[9]. They investigated the influence of factors such as the type of mesh, mesh layout, and the amount of reinforcement on flexural behaviour.

Shah and Naaman[10] felt that although ferrocement is a type of reinforced concrete its cracking is substantially different. They attributed this property to : (i) thinness of ferrocement element and distribution of reinforcement throughout the cross-section, (ii) the higher specific surface of mesh reinforcement, and (iii) the presence of transverse wires in the mesh reinforcement of ferrocement which enhances the bond transfer properties and crack characteristics.

Huq and Pama[11] proposed a method to analyse the ferrocement section in bending. In this they assumed linear variations for stresses and strains across the depth of cross-section. The stress-strain diagrams for the composite were idealized as elastic-perfectly plastic in compression and trilinear in tension. The moment-curvature curve was idealized as a trilinear curve. They then derived expressions for curvature, moment of resistance of ferrocement flexural member of rectangular cross-section, in the uncracked and cracked ranges.

Kumar et al[12] compared experimental deflections of 28 ferrocement beams with deflections obtained using ACI[13] and CEB code[14] formulae (for prediction of short-term deflection of reinforced concrete flexural members), in the working load range. From the experimental load-deflection plots obtained they noted that the load-deflection response of ferrocement flexural members can be represented by a tri-linear curve. They proposed, using the law of mixtures, a method to estimate the flexural rigidity of ferrocement beams. The comparison of estimated deflection with experimental values showed good agreement. They concluded that ACI and CEB formulae are quite suitable for prediction of effective flexural rigidity of ferrocement beams in the cracked range.

Based on static and fatigue tests on ferrocement flexure specimens, Naaman[15] proposed equations to predict maximum crackwidths. For static loading case the maximum crackwidth was found to be a function of stress in steel while in the fatigue loading it was found to be a function of maximum crackwidth under static load, stress range in the outermost layer of steel and cycle ratio (defined as the ratio between number of cycles at which maximum crackwidth is calculated and the number of cycles to failure).

Naaman[16] presented general guidelines and criteria that can be used in the design of ferrocement structures. He summarized and updated previously published work and presented a new section on design requirements and satisfactory performance.

Desayi et al[17, 18] presented the results of an experimental and semi-analytical study on the strength of trapezoidal cross-section roofing elements. The variables considered in the study were span to depth ratio, amount of longitudinal steel, and the type of mesh wire. They proposed methods to predict cracking and ultimate moments, and a bilinear load-deflection relation to predict the deflections under working loads. From the examination of load factors based on limiting deflection and limiting crackwidth, they opined that the former criterion may be critical in the design of roofing elements. A similar study was carried out, by Desayi *et al* (67, 89) on channel cross-section floor elements, and similar conclusions were drawn.

Yen and Su[19] tested 21 ferrocement specimens of varying width and varying thickness under central point loading to study the effect of skeletal steel on their strength. The number of layers of hexagonal mesh wires present above and below skeletal steel was also varied. The experimental cracking and ultimate loads of all specimens were obtained. Equilibrium of forces and moments based on conventional stress-block analysis was carried out to predict the behaviour in flexure. From these experiments they found that : (i) skeletal steel in the vicinity of the centroidal axis will have no significant effect on cracking moment although it significantly increases the ultimate moment, (ii) the introduction of skeletal steel also increases the ductility of the section, and (iii) the increase in ultimate moment capacity of thinner sections reinforced with skeletal steel is more significant.

Simple equations to predict average and maximum crackwidths for ferrocement beams reinforced with wire meshes with rectangular openings were presented by Balaguru[20]. The crackwidth at any stage of loading was expressed in terms of specific surface, curvature of the beam at the load under consideration, curvature of the beam when extreme tension layer of reinforcement just starts yielding, depth of neutral axis and the total depth of the beam. It was concluded that : (i) specific surface and the curvature of the beam are the main parameters that affect the crack spacing, and (ii) stiffness contribution of mortar in the tension zone should be considered for crackwidth prediction (especially when the external moment is comparable to the cracking moment of the beam).

Twenty laboratory size specimens of ferrocement strips, beams and lintels were tested by Kaushik et al[21], to study the effect of type of mesh reinforcement (viz. square woven and hexagonal woven) on the ductility, cracking moment, and rotational capacity of the hinging sections in the inelastic range. The two types of boundary conditions considered were restrained and simply supported while the two types of cross-sections considered were Ell and Tee. Assuming a nonlinear stress-strain relationship for mortar, trilinear relationship for moment-curvature response, and a perfectly elastic and perfectly plastic stress-strain curve for steel, they derived expressions for rotation, deflection and ultimate moment of resistance. They also proposed equations to predict crack spacing and crackwidths in ferrocement beams. The following conclusions were obtained: (i) with the increase in the volume fraction of mesh, the moment of resistance increases while the ultimate rotations decrease, (ii) the deflection at the centreof the restrained beam is about 40% to 55% of the simply supported beam, (iii) the available rotation capacity at the critical hinging location is significantly greater than the required rotation capacity, (iv) the proposed equations for crack spacing and crackwidths can be used to predict the same in ferrocement restrained and simply supported beams, (v) the average crack spacing at ultimate is significantly affected by the size and specific surface of the mesh reinforcement, and (vi) the maximum crackwidth at the mid span of the restrained beam is 60% to 70% of that of simply supported beam.

Due to thinness of ferrocement elements the serviceability criteria may govern their design. Kuczynski[22] discussed the phenomenon of deflection and cracking in ferrocement flexural members considering the law of continuous decrease of rigidity of flexural member under the effect of increasing load. Equations were proposed to determine the deflections under short-term and long-term loading. Allowable crackwidths of ferrocement structures under different service loads and methods to determine the elongation in the tension zone for such loadings were also given.

To study the influence of mesh-mortar ratio on the limit state behaviour (viz. deflections, cracking, cracking and ultimate load carrying capacities) of ferrocement flexural members, Trikha et al[23] conducted experiment on 150 prefabricated ferrocement elements like beams, strips, lintels, ribbed slabs and grid roof/flooring units. In order to predict the strength and behaviour of tested elements they used reinforced concrete theory in which (i) the stress-strain curve of mortar was assumed to be elastic-plastic, (ii) the composite stress-strain curve was assumed to be trilinear in tension and elastic-plastic in compression, and (iii) moment curvature diagram was approximated by a trilinear curve. The theoretically predicted responses compared satisfactorily with the experimental results. From the above study they arrived at the following conclusions. (i) The value of mesh-mortar parameter can be represented as a function of volume fraction of the element, specific surface, tensile strength of mesh reinforcement and skeletal steel, and the mortar strength. (ii) The first crack stress of ferrocement is a function of specific surface ratio of the mesh, the ultimate bending tensile stress of extreme layer steel, and the compressive strength of mortar. (iii) Crackwidth increases with the decrease in the mesh-mortar parameter.

Jiang[24] tested a total of ten ferrocement T-beams under symmetrical twopoint loading. The variables considered in the experimental study were number of layers of woven square wire mesh and the spacing of skeletal steel. From the experimental results Jiang presented a relative moment-strain characteristic relationship comprising of three working stages, namely elastic, elastic-plastic and yield stages. It was found that the ratio of the cross-sectional area of mesh wire to skeletal steel percentage reinforcement of the flange in the loading direction has an important effect on the development of cracks in the elastic-plastic range. A semi-empirical relationship was proposed to predict the maximum crackwidth of T-beams. Using a tri-linear curve for moment-curvature relationship, the mid span deflections were calculated. The computed deflections underestimated the experimental deflections and the average deviations were in the range 10% to 30%.

Desayi and Ganesan[25, 26] proposed methods to predict the spacing and widths of cracks in ferrocement trapezoidal roofing and channel type floor elements. The method, in general, was similar to the one proposed in [27]. However, some modifications related to ferrocement were introduced. The equations for crack spacings and crackwidths were derived by considering the equilibrium of forces at a cracked section. By comparing the strains computed using linear elastic theory with experimental strains, they found that the presence of tension flange in case of roofing elements affect the strains. Hence, they proposed a correction factor for the computation of strains. The constants appearing in the proposed equations were determined, in such a way that the average of the ratio of calculated maximum crackwidth to the experimental maximum crackwidth was close to unity. The computed lines of maximum crackwidth formed envelops of almost all observed crackwidths. This indicated that the method predicted an upper bound value of the maximum crackwidth. Analysis similar to the one described above was also carried out in Ref.[28] for built-up I-Joists[29 – 31], and equations for tension flange correction factor, crack spacing and crackwidths, were proposed.

Swamy and Spanos[32] studied the creep behaviour of ferrocement sections by conducting tests on ferrocement slabs. The slabs were simply supported and were tested under symmetrical two-point loading (loads applied at 1/3 span points). The type and amount of mesh reinforcement was varied, and both a cement and cement-fly ash matrix were used. The specimens were loaded at 28 days, and to stresses of 15%, 30% and 50% of their ultimate flexural strength, determined from modulus of rupture tests. The time under load was adjusted so that the creep deformations had stabilized, and it varied between 80 and 365 days. The specimens were then unloaded, and deformation recovery was monitored for about 30 days; and then they were tested to failure. From the results of the experiments conducted, it was concluded that : (i) deflection could be a major design parameter with ferrocement, (ii) instantaneous deflection is more critical than long-term deflection, (iii) the mesh reinforcement present in ferrocement helps in controlling cracking and reduces the slippage at cracks under sustained load, (iv) fly ash mixes show earlier stabilization of creep strains, (v) the transverse wires of the mesh reinforcement reduce the lateral strains in ferrocement (compared to plain mortar) under sustained loading, (vi) the high strength and welded mesh control cracking better under creep, (vii) cracking may not be critical criteria to be considered under sustained load, (viii) prolonged sustained loading has no adverse effect on ferrocement flexural strengths.

The use of efficiency factor of reinforcement (which depends on the mesh system and direction of loading), effective modulus of the reinforcing mesh system, standardized minimum yield strengths for different types of meshes, and application of ACI code[13] procedures for the design of ferrocement flexure elements was recommended in[33]. The computation of the moment of resistance of ferrocement using this method can be time consuming unless a computer is used. Hence, Naaman and Homrich[34] proposed a general methodology for the analysis and design of flexural members. They applied results of an extensive computerized evaluation of nominal flexural resistance to derive design aids in the form of a nondimensionalized design chart and prediction equation.

Mansur and Paramasivam[35] proposed a simple method to predict the ultimate strength of ferrocement in flexure, based on the concept of plastic analysis in which ferrocement was considered as a homogeneous, perfectly elastic-plastic material. This method is simple to use compared to those proposed by Logan and Shah[4], Jhonston and Mowat[6], Rajagopalan and Parameswaran[5, 36], Kumar and Sharma[7], Balaguru et al[8], and Huq and Pama[11], because, it does not involve any trial and error approach. They[35] derived expressions for ultimate moment of resistance of ferrocement flexural members having reinforcement arranged in three possible ways, namely, (i) reinforcement distributed uniformly throughout the cross-section, (ii) reinforcement lumped together in the tension zone, and (iii) reinforcement placed both in the tension and compression zones. An experimental investigation was also conducted to study the behaviour and strength of ferrocement in flexure. From the experimental and theoretical studies the authors concluded the following: (i) the first crack and ultimate moment increases with the decrease in water-cement ratio and increase in volume fraction of reinforcement, (ii) lower matrix grade and higher volume fraction of reinforcement improve the cracking characteristics, and (iii) the proposed method gives satisfactory predictions of the ultimate moment capacity.

Balaguru et al[37] proposed an analytical model to determine the ductility of ferrocement subjected to flexural loading. The model was based on an assumption that the beam failure occurs when the strain in extreme tension reinforcement reaches its fracture strain. They recognized that the fracture strain of reinforcement depends on type of mesh (woven or welded), spacing of wires, type of manufacture and type of cut and assumed a value of 0.015 mm/mm for the fracture strain. They developed a computer algorithm to estimate the curvature at ultimate (which involved a trial and error method to establish equilibrium of forces) and evaluated the model using experimental results. From a parametric study they found that : (a) variation of curvature with respect to fracture strain is linear, (b) fracture strain and thickness of beam affect the failure curvature significantly, and (c) the number of layers of mesh reinforcement (if greater than or equal to 4 layers) and the type of distribution of reinforcement have little influence on ductility of beam.

Hanai et al[38] presented in some detail the various clauses considered in the development of Brazilian ferrocement code. The recommendations made in general followed the CEB-model code (45). The authors felt that the specifications in the proposed ferrocement code can be revised by studying the performance of the ferrocement structures constructed using codal provisions.

Prakya and Morely[39] conducted four point bending tests on 8 ferrocement elements. The objectives of their study were : (i) to investigate the stiffening effect of mortar matrix and to study their behaviour with respect to the orientation of mesh to the principal bending direction, and (ii) to develop a simple equation based on the experimental data to compute the mean strains in flexural members, which can be used in estimation of crackwidths in the serviceability range of loads. From the experimental moment versus strain plots they inferred that the behaviour of ferrocement is similar to that of reinforced concrete. They also concluded that the mortar withstands tension even after cracking and that the tension stiffening effect increases with the increase of angle of reinforcement with the principal bending direction. A simple formula based on the experimental results was proposed to evaluate mean strains in the flexural members which can be used in estimating crackwidths and deflections.

Based on experiments conducted on ferrocement subjected to pure flexure and pure shear, and test data available in the literature, Vaidyanathan and Perumal[40] studied various characteristics of ferrocement. They also pointed out factors influencing the strength and behaviour of ferrocement elements.

While the afore presented brief review gives an idea about the research carried out to understand the strength and behaviour of ferrocement flexural elements in 1980s and continued in 1990s[41, 42], most of the methodologies to predict the same have now become standard for example[43 - 45].

The research in the field of ferrocement has been progressing very fast and the papers presented during symposia on ferrocement bare the testimony for the developments. For example, the themes of FERRO14 symposium[46] are: Innovative Materials and Technologies, Modeling, Analysis, Design, and Construction, Applications, Case Studies, and Innovative Projects, Durability, Sustainability, and Life Cycle Cost Analysis, Repair, Strengthening, and Rehabilitation of Existing Structures, and Ferrocement Housing for Natural Disaster Mitigation. The papers presented in FERRO 14 were, in general, followed the futuristic predictions made by Naaman[1].

In India, like in other countries, efforts are being made by Building Materials Technology Promotion Council (BMTPC) to promote the use of ferrocement panels in the design of buildings. BMTPC also provides performance appraisal certification for use of ferrocement panels as a part of ferrobuild design systems[47, 48]. Similar efforts to popularize ferrocement technology, are also being made by Maharastra Engineering Research Institute[49] and CSIR – SERC (Council of Scientific & Industrial Research - Structural Engineering Research Centre, Chennai)[50]. While these efforts are helping promote ferrocement technology, the absence of an accepted international/national code is the need of the hour to promote the use of ferrocement in construction by amateur and self-help groups.

Due to variations in cross-sectional dimensions, strengths of materials used and loads incidenting, the strength and behaviour of ferrocement flexural members vary. From the review of literature on strength and behaviour of ferrocement it has been found that there is scant literature on probabilistic analysis of ferrocement flexural elements. Carrying out such an analysis is a step towards development of LRFD codes for ferrocement[51]. Keeping this in view, the studies reported in this paper are taken up.

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