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A simplified non-linear analysis of concrete frames*

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Contribution by Bernard Espion

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The authors are to be congratulated for bringing some very useful experimental data to people wanting to calibrate numerical models for computing the time-dependent behaviour of reinforced concrete frames. In a previous paper (reference 9 of their paper), they had already noted that "there is little well documented data from tests on prototype-sized frames" and this is the reason why the data from frames 3F1 and 3F2 are specially welcome. The writer's contribution will focus on the following points:

(1) supplementing the authors' reference list with some works in the field of computer programs capable of performing with beam finite elements the geometrically non-linear and time-dependent analysis of reinforced concrete plane frames;
(2) commenting on the modelling of the frame tests devised by the authors and more precisely on the choice of the prediction model used for the analysis;
(3) commenting on the use of Branson's formula in combined bending and axial force.

OTHER PUBLISHED DATA

The authors have referred in their paper to only two "refined computer-based methods for the analysis and prediction of the non-linear and time-dependent behaviour of cracked reinforced concrete frames under sustained loading"[1,2]. The contributor wishes to add to this list the methods also proposed by Chovichien *et al.*[12], Aldstedt[13,14], Kang[15,16], Ferraro Maia[17,18], Bažant and Tsubaki[19], Chow[20,21], Ožbolt[22] and the writer himself[23–25]; a review of the algorithms used in these programs has been given in Reference 23.

It is interesting to mention that, before the frame tests 3F1 and 3F2 conducted by the authors, researchers had very little reference data at their disposal to calibrate their models with frame tests under sustained loading. Calibration was therefore essentially achieved with sustained tests on beams and columns. The tests by Drysdale[11] simulated by the authors were also analysed numerically by Ferraro Maia[17,18] but it must be pointed out that these frames were not very sensitive to time-dependent effects.

COMMENT ON THE FRAME TESTS BY THE AUTHORS

In a previous paper[25] we have already used the experimental data from frame 3F2 tested by the authors to calibrate our own numerical model. At that time, we referred to an earlier numerical analysis by the authors[9]. It is quite surprising that the authors have obtained a far better prediction of their tests with a simpler approach than the first one[9] which accounted for geometrical non-linear effects.

We feel that frame tests 3F1 and 3F2 are very

*Pages 29 to 34 of MCR 138.

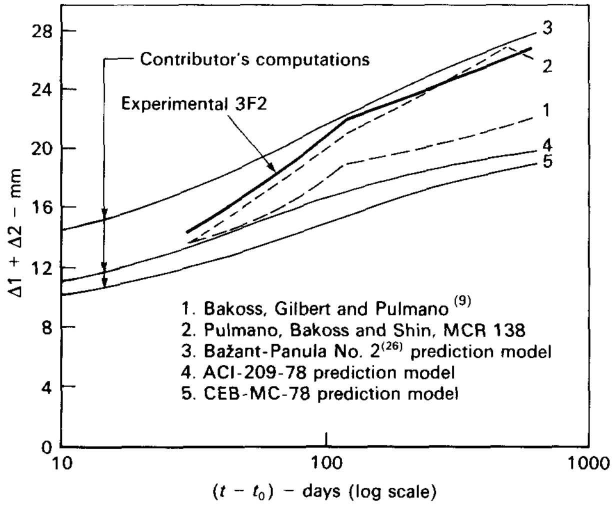

Figure I: Contributor's computations with full codified prediction models.

interesting because, as we will show, they are highly sensitive to the choice of the creep and shrinkage functions used for the prediction of the time-dependent concrete strains.

Our model[(23–25)] takes into account geometrical non-linear effects, and tension stiffening is introduced through a smeared approach. The time-dependent analysis uses the general superposition algorithm based on the numerical evaluation of the hereditary integral of linear viscoelasticity with a trapezoidal rule. The analysis may be run either with general ageing and codified prediction models (CEB-MC-78, ACI-209-78, Bažant-Panula[(26)]) or with simple non-ageing prediction models whose parameters are adapted in consideration of the particular experience to be modelled.

Figures I and II present some computations[(23,25)] using various creep and shrinkage models which were obtained by dividing the structure into 500 mm long beam elements. It should be stated that frame 3F2

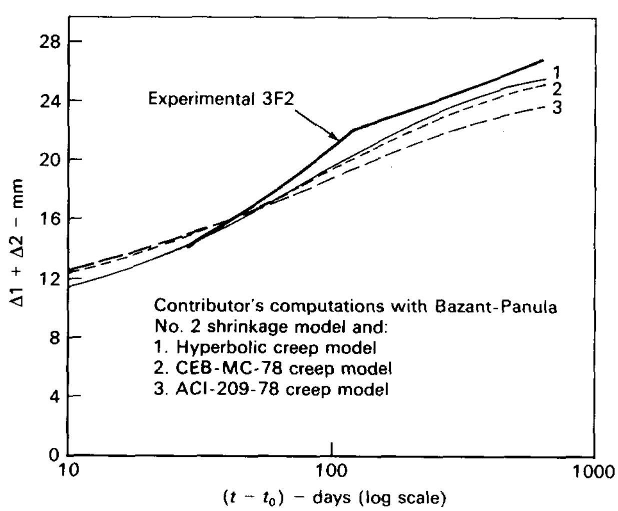

Figure II: Contributor's computations with mixed prediction models.

cannot be analysed properly without taking due account of shrinkage and tension stiffening effects; they are very important in this structure because the shrinkage strains are rather high (660×10^{-6} after 532 days[(9)]) and also because the columns are singly reinforced and therefore differentially curved. Secondly, it is observed that computations with ACI or CEB models grossly underestimate the long-term displacements; this is mainly due to the poor prediction of the shrinkage strain achieved by these two models in this experiment (Figure I); in fact, a superior prediction is obtained with the ACI and CEB creep models by coupling them with the Bažant-Panula No. 2[(26)] shrinkage model (Figure II). Finally, the best overall prediction is obtained with a "mixed" model composed of the Bažant-Panula No. 2 shrinkage model[(26)] and of an experimental creep model of the kind used by the authors (Ross' hyperbolic) to match their own creep curve:

$$J(t, t') = \frac{1}{E_c}\left\{1 + \phi_\infty \left[\frac{(t - t')}{t_{1/2} + (t - t')}\right]\right\}$$

with $E_c = 27300\,\text{N/mm}^2$; $\phi_\infty = 2{\cdot}83$; $t_{1/2} = 88$ days.

BRANSON'S FORMULA

The authors have used the well-known proposition by Branson to compute the effective bending stiffness. This empirical formula has mainly been derived from simple bending tests[(3)] and its extension to cases with combined bending and normal force has been limited only to cases of constant eccentricity M/N[(27)] and partial prestressing[(28,29)]. It seems that the authors have restricted their modification of Branson's formula to cope with the presence of the normal force by introducing the influence of N on the cracking moment (Equation 6). The contributor wonders if such a simple approach is sufficient to represent the moment–curvature relationship of reinforced concrete sections under combined bending and normal force. In fact, for such cases, which are common in frames, the assumption of a linear fully cracked state II (I_{cr}) is no longer valid because the position of the neutral axis in the cracked state II is highly dependent on the eccentricity M/N.

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Reply by the authors

We wish to thank Dr Espion for his comments on our paper. Our responses are numbered to correspond with the numbering of his comments.

(1) The purpose of the paper was, as the title implies, to provide a simplified method for the analysis of the non-linear behaviour of concrete frames. Consequently the literature on "refined computer-based methods for the analysis and prediction of the non-linear and time dependent behaviour of cracked reinforced concrete frames under sustained loading" was not comprehensively reviewed. References additional to those listed by Dr Espion may be found in Reference 9.

(2) The second-order non-linear geometric effects due to axial loads that were accounted for by the authors in the procedures described in Reference 9 do not have any significant influence on the deflections of the test frames. Consequently it should not have been surprising that the omission of this refinement did not degrade the validity of the deflections predicted by the proposed simplified method.

The authors agree with Dr Espion that the test frames are sensitive to the time-dependent effects of creep and shrinkage; this was one of the main objectives in the design of the prototype testing programme. Further, the authors' work also shows[10] that the reliable prediction of the long-term behaviour of concrete skeletal structures requires reasonably accurate knowledge of the in situ creep and shrinkage characteristics. In the present study extensive material testing was carried out on companion specimens whose cross-sections were identical with those of frames 3F1 and 3F2, in addition the creep and shrinkage specimens were subjected to the same curing and environmental regimes as the frames. This was done to ensure that the differences between the predicted and actual frame behaviour were a measure of the accuracy of the proposed method and not a consequence of errors in the material properties used.

Although the given hyperbolic expression (9), for the time rate of creep development was found to agree well with measured values, other models have also been shown to give satisfactory agreement with values obtained from tests[30]. The authors have also found that the CEB model in all cases grossly under-estimated the unrestrained shrinkage strains.

It should be recalled that the objective of the paper is to present a simplified method for the analysis of the long-term behaviour of low-rise concrete frames, suitable for application by designers. The prediction of the creep and shrinkage properties of plain concrete, whilst very important to such analyses, is not a central issue addressed in the paper.

(3) The definition of the cracking moment M_{cr} in Equation (6) agrees with that given by Branson and Trost[27,28] for partially prestressed beams. In the presence of axial forces they found that the effective moment of inertia of a partially cracked section was adequately represented by the cubic expression (5) providing that the bending moment at the section was taken as the net moment. There is no doubt that neutral axis shifts in cracked columns are a function of the M/N ratio, however, the relevance of the last sentence of Dr Espion's comments remains unclear.

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An investigation of the pozzolanicity and hydraulic reactivity of a high-lime fly ash*

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Contribution by John B. Ashby

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I was very interested in the paper by Joanna Papayianni in relation to Australian lignite fly ash. As she mentions, lignite fly ash is produced in Australia. In fact, the State of Victoria produces large quantities of fly ash from the burning of lignite coal. Beretka[1] reported that over 300,000 tonnes of lignite fly ash was produced in 1976 in Victoria.

However, Australian experience in attempting to use local lignite fly ash in concrete has not been satisfactory. Concrete has been found to expand significantly and unpredictably. This expansion has been noted at the time test specimens were being removed from their moulds at the age of 24 h after being stored under wet hessian at an ambient temperature in the range 20 to 25°C. The actual expansion was not measured. These test specimens were also characterized by a coating of white crystals considered to be due to the high percentage of soluble salts contained in the fly ash.

Beretka[1] has reported that the lignite fly ash from these sources had a high proportion (25–40%) of soluble salts such as chlorides and sulphates of calcium and magnesium. Research on these materials was discontinued in favour of fly ashes giving more promising results. Beretka has reported also that these lignite fly ashes have poor pozzolanic properties. Typical analyses of two sources of lignite fly ash reported by Beretka[1] are as follows:

Constituents (weight%)	Source	
	Hazelwood	Newport
SiO_2	13·0	9·3
Al_2O_3	4·5	11·7
Fe_2O_3	12·0	30·0
CaO	33·0	9·5
MgO	16·0	24·0
Na_2O	4·5	5·0
K_2O	0·3	0·3
SO_3	14·5	8·5

The author states that the ground lignite fly ash performed very well as a pozzolan and also cites earlier work (reference 4 of the paper) which showed that a high SO_3 content was not detrimental. Our experience with the Victorian fly ashes is not as favourable as the author of the paper has reported of Greek fly ash.

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*Pages 19 to 28 of MCR 138.