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COMMENTARY - 75 YEARS OF RILEM: MATERIALS & STRUCTURES

# M&S highlight: Bažant and Baweja (1995), Creep and shrinkage prediction model for analysis and design of concrete structures—model B3

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Reliable predictions of shrinkage and creep are of utmost importance for designing durable and safe concrete structures. Hence, these phenomena have always been among the top interests of the RILEM Community, with 6 Technical Committees devoted to them until now (TCs 069, 107, 114, 179, 242, and 261). An important period in RILEM's activities on creep and shrinkage occurred in the years 1995–1996, when a series of papers was published stemming from the works of the TC 107 "Guidelines for the formulation of creep and shrinkage prediction models" chaired by Prof. Z. P. Bažant. Among these, two papers have gained the most attention and have had an immense impact in the field. The first was "Creep and shrinkage prediction model for analysis and design of concrete structures—model B3" [1], a RILEM recommendation prepared by Bažant and Baweja in collaboration with RILEM TC 107 (Subcommittee 1) and ACI Committee 209 (Subcommittee 2). The paper has been cited over 440 times (Web of Science Core Collection, July 2021). This means that it has been cited in about 10% of papers devoted to the topics of "creep" and "concrete" since then (overall of 4767 papers, Web of Science Core Collection, July 2021). The second, affiliated paper, was published in the same issue of Materials and Structures: "Justification and refinements of model B3 for concrete creep and shrinkage 1. statistics and sensitivity" authored by Bažant and Baweja [2], and it has been cited over 120 times.

The two papers are notable in particular because they address two extremely relevant aspects: (i) the need for a model that is practical as a design code recommendation, yet is based on the most advanced understanding of the underlying processes; and (ii) the calibration of the model based on a broad and (as much as possible) unbiased dataset, in fact most probably the largest dataset available at that time. In this short introduction I will briefly address both points.

At the time when the papers [1, 2] were published, the knowledge about the mechanisms causing shrinkage was already quite advanced, but no consensus had been reached with regard to creep of concrete (in fact, despite notable scientific advancements, it is still a

This commentary is part of our celebration of 75 years of RILEM, highlighting Materials and Structures most highly influential and cited publications.

Highlighted paper: Bažant, Z. P. & Baweja, S. Creep and shrinkage prediction model for analysis and design of concrete structures—model B3. Materials and Structures. (1995) 28(6): 357–365.

Affiliated paper: Bažant, Z. P. & Baweja, S. Justification and refinements of model B3 for concrete creep and shrinkage 1. statistics and sensitivity. Materials and Structures. (1995) 28(7): 415–430.

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challenging problem as I write). Yet, even without the ability to quantify the basic mechanisms, the prediction of creep and shrinkage effects in structures had always been critical for design purposes. In case of underestimated long-term deformations, the structures may suffer from excessive deflections and reduced serviceability. In case of extreme sensitivity to deflections, for instance in long-span bridges, even structural safety may be at risk. Hence, the topic is one prominent example where the activities of research communities, standardization societies and structural engineers converge.

At the beginning of the 1990s, computer-aided design of structures was gaining impact as the first software packages became internationally marketed and accessible on personal computers. At the same time, it became clear that the available sophisticated structural computations were only as reliable as the material models that they were based on. This was especially true for shrinkage and creep in high-end structures that could suffer from oversimplification in the design. The problem of insufficient consideration given to the effects of shrinkage and creep was illustrated by Bažant and Baweja in very sharp yet illustrative words:

> *[…]it makes no sense for the analyst to spend weeks on the structural analysis while spending half an hour to determine creep and shrinkage properties to use as the input* [2].

This is why a new predictive model of shrinkage and creep was urgently needed at that time. This need perpetuated the work of the aforementioned two international Technical Committees: RILEM's TC 107 (continuing the work of the previous TC 069) and in parallel ACI 209. In fact, many researchers were actively contributing to both committees at the same time.

Different criteria have been defined that a creep and shrinkage model should meet to be compatible with structural design purposes [3, 4], where the final model form would be a compromise between the scientific rigor, the simplicity of implementation and representativeness of a broad range of concrete mix designs, environmental conditions, geometries etc. The notable prediction models that existed at that time and were adapted in different design codes actually violated these guidelines, for instance: ACI 209 model from 1971 and updated in 1992, and the CEB model from 1990 (that would be updated in 1999), see [5, 6]. The Model B3 was a successor of the previous two models developed at Northwestern University, USA: the BP model from 1978 [7] and the BP-KX model from 1991 [8]. It was simpler in implementation than the previous two but at the same time more theoretically sound. The B3 model offered in general more reliable predictions than the previous models, in particular because in many cases they underestimated the long-term deflections [5, 6]. The better fit with experimental data was obtained by the novel way the model was calibrated. Besides being based on the largest database at that time (this topic deserves a special deliberation later on), the novel statistical treatment of the data was key. Although the model calibration relied on a rather standard minimization of the squared error, it is how the long-term data were rigorously treated that secured the model's reliability. It is a common feature of most shrinkage and creep experiments that the measurements are carried out at highest frequency at early ages, when the deformation rate is the highest, while less frequent at later times (not to mention a general lack of truly long-term measurements beyond a couple of years). Yet, it is the long-term prediction of deflections that matters the most for design purposes. The authors of [1, 2] addressed this issue by assigning weights to the measurements split into decades in logarithmic scale. Such approach allowed for a good trade-off in fit of both short and long-term shrinkage and creep.

The theory of shrinkage, and even more so, of creep of concrete had not then and has not until now experienced any particular rapid breakthroughs. Instead, it has been a gradual, but consequent process since the pioneering works in 1950s–1960s, e.g. [9–14]. The model B3 was based on the most up-to-date at that time developments in the field. It predicts creep in the form of the compliance function based on the superposition principle, with explicit accounting for the aging basic creep and drying creep, both processes better founded theoretically than in the previous (and also in some later) models [5, 6].

Yet, as said, even though the mechanisms adopted in the model made it more advanced and rational, the improved prediction power that guaranteed the success of the model was most likely due to yet another major reason—the statistically advanced and rigorous way the model was calibrated.

Any model that aims at satisfying the needs of structural designers needs to account for the dependence of creep and shrinkage on the material properties of concrete and its mix design. In the model B3 this was addressed with 5 linear parameters for creep ($q_1 \ldots q_5$) and one non-linear parameter for shrinkage (shrinkage half-time). The most prominent feature of the model B3 was that these parameters had been calibrated based on a dataset of an unprecedented scale. The collection of data from shrinkage and creep experiments from around the world had started at Northwestern University, USA, at the beginning of the 1970s. The first database had been compiled in 1978 with about 10 000 data points [7]. The database was next extended in 1993 to what became known as the RILEM Databank under the auspices of the RILEM Committee TC 107 (subcommittee 5 chaired by H. Müller) and the ACI-209 Committee. That database consisted of over 500 creep curves and over 400 shrinkage curves from − 100 test series, with overall 15,000 data points [2]. The curation of the dataset was truly visionary and anticipated current trends of data science methods in concrete research, leading to further extensions of the database (about 40,000 data points reported in 2015 [15]).

For a model that is well validated against external conditions (load, humidity, temperature), the major source of uncertainty of prediction remains still in the uncertainty of its material parameters. Together with the better fit, the large database also allowed to genuinely estimate the statistical uncertainty of the model B3 parameters. Namely, 95% intervals were reported in [2] as $1 \pm 0.45$ for creep parameters and $1 \pm 0.67$ for ultimate shrinkage strain. This gave practitioners a genuine indication up to which extent the model predictions can be relied upon, a feature still often lacking in sophisticated predictive models. Although the calibration data limited the application of the model to ordinary concretes, the model specifically allows for recalibration of the parameters and better prediction power based on short-term creep measurements. A feature pivotal for that task is that the 5 parameters responsible for creep description ($q_1 \ldots q_5$) enter the model linearly. Hence, the recalibration of the model can be done straightforwardly with the use of linear regression methods.

The model proved its versatility for both simple calculations and more complex approaches in the following years. For less sensitive structures the model could be integrated into a one-step solution, e.g. (age-adjusted) effective modulus method, especially in its simplified form published soon after [16]. At the same time, it could be applied for elaborate models where the superposition principle is satisfied with numerical integration and the cross-section effects of moisture and temperature gradients are addressed with the Finite Element Method, e.g. [17]. The versatility and wide validation of the model paved the way for future developments, namely the model B4 [18]. The latter model was created also under the auspices of RILEM and was a recommendation of RILEM TC 242- MDC especially to meet the risk of excessive multi-decade deflections in bridges [19].

Having listed different highlights, it is perhaps sufficient to state as a closing remark that although the model B3, as any other model, has its limitations, it has proven to successfully merge the two different and often competing modelling approaches: as a rational academic-type model and as a reliable, statistically validated design tool for civil engineers. The merging of the two realms, the academic and the engineering one, agrees perfectly with the general strategy of RILEM since its creation 75 years ago.

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