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SAFETEA-LU Project
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FINAL REPORT

Rational and Safe Design of Concrete Transportation Structures for Size Effect and Multi-Decade Sustainability

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DISCLAIMER

ABSTRACT

The overall goal of this project was to improve the safety and sustainability in the design of large prestressed concrete bridges and other transportation structures. The safety of large concrete structures, including bridges, has been insufficient. This is evidenced by the worldwide rate of failures of very large concrete structures which has historically been about 1 in a thousand per lifetime, although 1 in a million is the maximum tolerable. Improvement necessitates taking into account the size effect on quasibrittle failure loads, a phenomenon that has been mostly ignored by the ACI code committee until recently, but now is considered seriously, largely as a result of this project.

The multi-decade durability has been rather poor for the segmentally erected prestressed concrete box girder bridges, many of which deflected within about 20 to 40 years several times more than expected in design. Significant improvements in multi-decade prediction of creep and shrinkage and their effects in bridges have been achieved under this funding. They aim at: • design practice, • computer programs for engineering practice, including commercial codes, • design codes or standard design recommendations (ACI, AASHTO, RILEM, *fib*), • interpretation of measurements on monitored structures, • predictive material model formulation, • material testing standards (ASTM, RILEM, fib), and • design aids.

The research carried out consisted of 11 tasks. Painstaking data search has led to a collection of excessive deflection histories of 69 large-span prestressed segmentally erected box girders. This proved that the hypothesis of existence of an asymptotic creep bound, used in all standard recommendations, is incorrect. Interpretation of the monitored deflections is a statistical challenge, aggravated by insufficiency of revealed data. An inverse statistical approach with sensitivity analysis and nonlinear optimization, combining the multi-decade bridge deflection histories with the NU-ITI database of shorter-time laboratory creep tests (to be enhanced by extensive data from collaboration with JSCE, Japan), has been used to extract the creep model parameters and find their correlation to concrete composition and strength (Tasks 1 & 2). The bridge simulations and deflection monitoring also revealed the need for a better constitutive law for prestressing steel relaxation at variable strain and temperature. A viscoplastic flow law with activation energy has been formulated and calibrated by test data from the literature, mainly from the nuclear industry research (Task 3). The age-adjusted effective modulus method for simplified analysis of structural creep and shrinkage effects, devised by the PI and enshrined in the ACI and *fib* standard recommendations, has been improved for multi-decade creep using asymptotic conditions (Task 4). In ACI Committee 209 (and in *fib*) (Tasks 1-3) the PI argued for adoption of the resulting improved prediction model, and for standardization of rate-type creep analysis (Task 5), and a committee with this task was formed. To enable designs satisfying a specified maximum tolerable failure probability (10^{-6}), the size effect on the type of strength and lifetime distributions of quasibrittle structures has been analyzed (Task 6). An unprecedented series of size effect fracture tests of 140 specimens of widely different sizes and notch depths, all cast from one and the same batch of concrete, has been completed. It led to the formulation and validation of a universal size effect law for quasibrittle failure (Task 7). This work has been extended to size effect formulations for shear failure of beams with stirrups, to torsional failure of beams, and to punching shear failure of slabs. Arguments were made in ACI committees 446 and 445 for introducing the size effect into the ACI design code, along with supporting failure probability assessments (Task 8). Under Task 9, a new open-source design aid has bee developed and is now to be posted on our ITI website. Task 10 provided argumentation to convince ACI, ASTM & RILEM to standardize a fracture test, with only a partial success so far. Task 11 aimed at persuading ASCE, ACI and NAE Civil Engineering Section to adopt or recommend an ethics code condemning concealment of technical data from major structural failures or damages, with success so far only in the NAE.

Nature of Problem Studied

The problems of multi-decade sustainability and the problems of safety against collapse or major damage of concrete structures have not been properly reflected in the infrastructure design practice, computational tools and design codes. Since concrete is replacing steel as the material of choice for large structures such as bridges (as well as very tall buildings), these problems are becoming more important.

Safety

Based on the probabilistic studies of hazards to which people are exposed, engineering structures such as bridges, as well as aircraft and ships, must be designed for failure probability of less than 1 in a million per lifetime. Statistics show that this requirement is indeed satisfied for normal size concrete structures, if human errors, poor quality control and negligence are not counted. However, world-wide statistics collected by Melchers and by the Nordic Concrete committee show that large concrete structures have been collapsing worldwide at the rate of about 1 in a thousand. The greatest risk and the main cause of collapse of large structures is the brittle failure, which in reinforced concrete occurs primarily under shear loading and is aggravated by size effect.

Whereas structural design is not yet based on assessment of failure probability, the studies under this grant showed that if the size effect on shear failure of reinforced concrete beam designed according to the ACI-318 Standard is not taken into account, the failure probability increases from 1 in a million to 1 in a thousand for some large beams that have been built. This tends to agree with the aforementioned statistics. While some such beams have recently been built, such a level of failure risk is unacceptable. A revision of design practice, including the design code, is therefore required, especially since the modern concretes are not only stronger but also more brittle. The way to do that has been demonstrated.

Sustainability

The multi-decade creep of concrete is more important for sustainability and durability than has been thought. It leads to excessive bridge deflections with cracking, which cause problems within 20 to 40 years, while the lifetime is typically required to be >100 years. The problem is particularly acute for large-span segmentally erected prestressed concrete box girder bridges, which have been invented and built in Europe since the 1950s and used in East Asia since the 1970s. In the U.S., bridges of this type came to be widely designed and built only recently, although a few classical bridges of this type (e.g., Parrott Creek, Pine Valley Creek, Kishwaukee) exist. It is important to ensure that the lifetime of these large bridges would indeed exceed 100 years, as required by most DoTs.

The ITI funding led to the revelation that dozens, if not hundreds, of such bridges suffer greatly excessive deflection which either requires an expensive and risky retrofit with additional prestressing, or bridge replacement. Yet these problems are typically not revealed to the engineering public and are not sufficiently documented for analysis, apparently for fear of bad publicity. It does not help that, after the lapse of 20 to 40 years, the original designers are not, or cannot, be held liable, which might explain why the designers of such bridges appear not to be overly concerned, and allows obsolete standard recommendations on creep and shrinkage design to linger. A glaring paradigm for excessive deflections, as well as the fracture mechanics size effect, has been the ill-fated KB Bridge in Palau. Its analysis under this grant led to several new directions of research.

Size Effect

Concrete is one of the quasibrittle materials, the characteristic of which is a strong non-statistical size effect on both the structural strength (discovered at NU) and on the rate of creep and shrinkage (caused by size dependence of the drying rate). This kind of size effect is by now universally accepted by the IA-FRAMCOS and by the Engineering Mechanics Institute of ASCE, and also by the ACI Committees 446 (Fracture Mechanics) and 447 (Finite Element Analysis) which, unfortunately, have almost no say on the ACI design code formulation. Largely thanks to the evidence and activities sponsored by the NU-ITI, the size effect is now widely acknowledged to be a serious issue (even in the ACI code-making committees, ACI 318 and 445).

Although the reinforcement is the only plastic component of reinforced concrete, the basic design philosophy of ACI still remains to be the plastic limit analysis. During the course of this grant, the PI made proposals in ACI Committees 445 and 446 to introduce size effect. Although there has been much political resistance, the problem is now seriously debated, both for beam shear and for punching shear of slabs. The size effect has already been accepted in the code articles for the shear pullout of anchors.

Objectives of Research

I. Transfer advances in size effect, failure risk, and creep and shrinkage theories into practice, in order to improve the safety, sustainability and resilience of transportation structures.
II. Conduct research needed for this purpose.

More specifically, the objective of the PI (who is the only Registered Structural Engineer at Northwestern University) is the introduction of the recent scientific advances into:

1. design practice;
2. computer programs for engineering practice, including commercial codes;
3. formulation of predictive material models;
4. design codes or standard design recommendations (ACI, AASHTO, RILEM, *fib*);
5. interpretation of measurements on monitored structures;
6. material testing standards (ASTM, RILEM, fib); and
7. design aids to be made freely available at the ITI website.

To achieve this objective, the work tasks described below have been pursued.

Task 1. Multi-Decade Concrete Creep Properties and Their Identification from Incomplete Bridge Deflection Data Combined with Filtered Laboratory Database

The release of the previously sealed technical data on the excessive deflections of the world-record KB Bridge in Palau, which came about a dozen years too late and was forced by the ethics resolution of the Structural Engineers World Congress proposed by the PI, proved to be a gold mine. The results of our analysis, presented in detail in four 2012 papers in JEM-ASCE [5,6] and ACI Struct. Journal, [4, 9] demonstrate that the excessive deflections, which reached in Palau1.61 m and led to a risky and fatal retrofit, had the following causes, in the order of decreasing importance:

1. An incorrect concrete creep prediction model embodied in standard recommendations (a final asymptotic bound on creep does not exist; the terminal multi-decade creep is logarithmic, the drying creep effect is additive rather than multiplicative and consists in acceleration rather than strain scaling, etc.).
2. Entrenched use of obsolete one-dimensional beam-type analysis, instead of a three-dimensional step-by-step rate-type creep analysis that can capture all the types of shear lag and time-varying environment.
3. Incorrect modeling of the differential drying effects on both creep and shrinkage, conflicting with the diffusion theory.
4. Wrong estimation of prestress losses, including the relaxation of prestressing steel.
5. Ignorance of temperature effects on concrete creep and on steel relaxation.

Some researchers, including us, suspected also a major contribution from fatigue growth of microcracks giving rise to cyclic creep due to traffic loads. However, detailed analysis and a new model for cyclic creep, being now written as a paper to submit, proved that cyclic creep had a negligible effect in Palau, because the stresses were dominated by self weight, causing the ratio r of cyclic stress amplitude to the permanent stress to be too small. By analysis of test data, it was confirmed that the cyclic creep deflections grow as r^4. This conclusion, though, also implies that cyclic creep should have a large effect for medium span bridges of a span around 80 m, because the self weight does not dominate and thus r is large.

The result of the aforementioned five causes was a 3- to 4-fold underestimation of the 18 –year deflection according to the American, European and Japanese standard recommendations (Fig. 1). This result was confirmed by detailed three-dimensional step-by-step finite element creep analysis of the bridge in Palau, and subsequently of four Japanese bridges, which suffered similar excessive deflections (data obtained by courtesy of Y. Watanabe, chief engineer, Shimizu Co., Tokyo) [5,6].

A method of realistic analysis of multi-decade deflections has been developed and published [5,6,9]. It was shown that the observed excessive deflections can in fact be theoretically explained (although they were not correctly explained during the litigation). However, prediction of the multi-decade material creep properties guaranteeing reliable multi-decade estimates a difficult problem, which will have to be studied further. It necessitates predicting concrete creep properties from material composition. This further requires relating the parameters of a theoretically founded material creep and shrinkage model to the concrete strength and main composition parameters, which is a formidable task from the statistical viewpoint.

During the last year, we had some collaboration with the JSCE (Dr. Sakata, Tokyo) committee on creep (chaired by Dr. Ayano). Through their courtesy, we were able to enlarge our laboratory database by about 30%, containing now over 40,000 data points, with >1000 creep tests and >1000 shrinkage tests. However, a laboratory database is not enough for multi-decade creep prediction. A large majority of data (about 97%) refers to creep of less than 7 years of duration. Thus, for multi-decade creep, data on the multi-decade deflections of creep-sensitive structures must be used. Among these, the most useful are the data on excessively deflecting large-span segmentally erected prestressed concrete box girders [4].

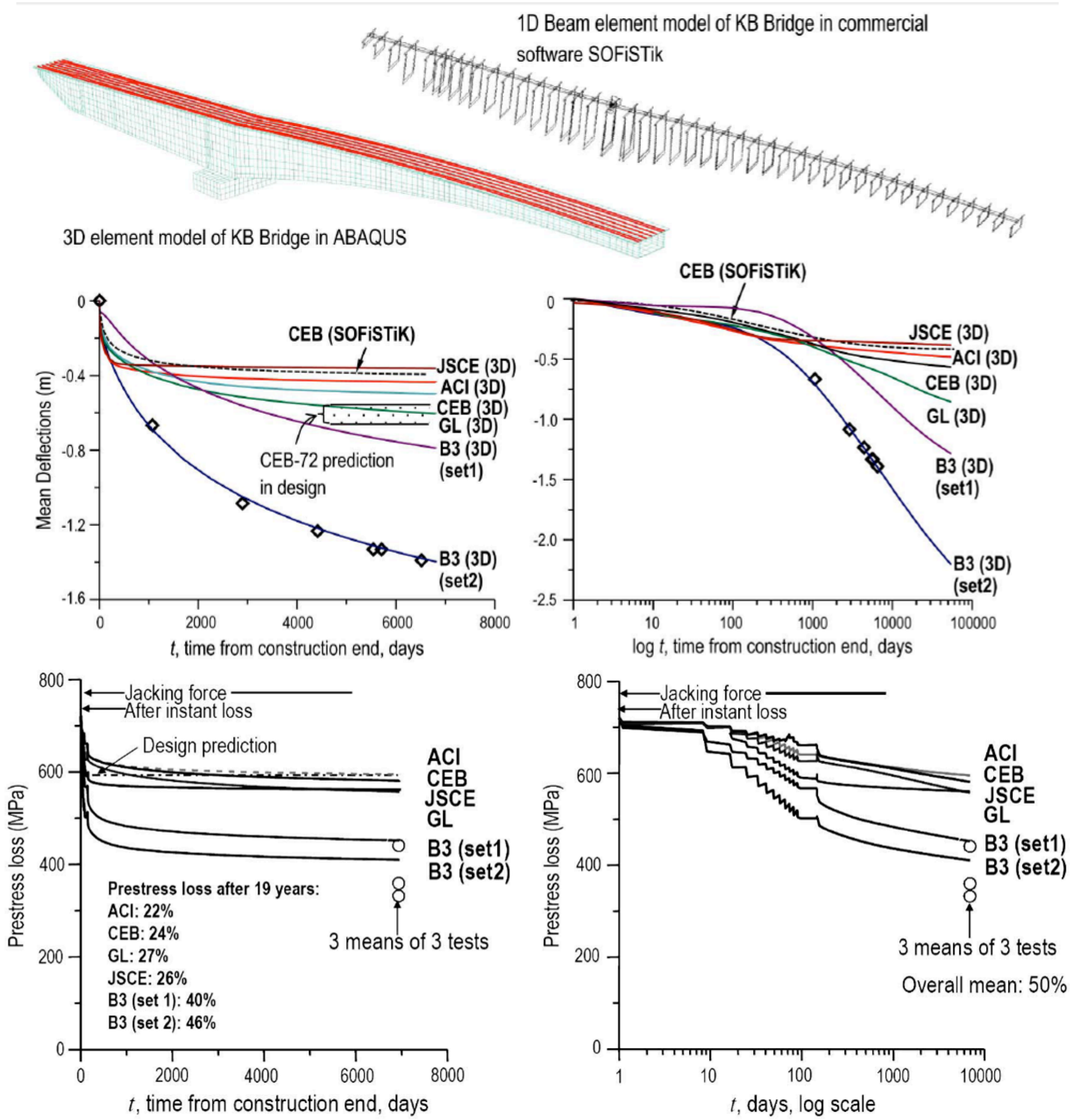

Fig. 1 FE discretization, and measured and predicted deflections of the world-record span of the KB Bridge in Palau (SOFiSTiK is the most popular commercial code for bridge creep at present)..

To help in this effort, the PI founded international RILEM Committee TC-MDC, Multi-Decade Creep, which he chairs. This effort resulted in a wake-up call. Already 69 excessively deflecting bridges have been documented (see 56 examples, from several countries, in Fig. 2). Probably hundreds more exist worldwide. It was a strenuous, painstaking effort. Most of these results were obtained from various reports and scattered papers, in which the excessive deflections were deplored without realizing their ubiquity. Worse yet, the proper conclusions have not been drawn (the blame being assigned, e.g., to "poor construction" instead of wrong standards recommendations).

An unexpected problem arose, however. With the exception of 5 segmental bridges, only very limited data, limited to the deflection history, could be obtained. It turned out to be impossible to obtain information on the geometry, type of concrete, prestressing forces, material tests, load tests, etc., which are necessary for inverse finite element analysis (reasons: apathy, endless procrastination, stonewalling, excuses, claimed loss of data, fear of negative publicity, etc.). Therefore, the original plan of research stated in a previous proposal had to be revised in several respects:

1. The deflection data from 64 (or more) bridges can be used only in the relative sense of the ratio of multi-decade deflection to the *n*-year deflection, perhaps the 1000-day deflection. For this purpose, an approximate formula to extrapolate the observed 1000-day deflection has been developed [4, 21].
2. Since the concrete composition for these bridges cannot be obtained, the statistical analysis must be based on the estimate of the usual concrete properties used at the time of erection. This will distort the standard deviation but not significantly the mean of the inverse inferences.
3. The bridge deflection data must be statistically analyzed together with the laboratory database, first iteratively and then jointly, so as to find the functional dependence of creep parameters on the composition and strength parameters of the material.
4. A genetic algorithm, as described in the previous proposal, may have to be coupled with the statistical methods of sensitivity analysis, to aid identifying the form of the aforementioned functional dependence, before this dependence is optimized quantitatively.

Two papers on items 2—4 are in preparation.

The result of this work is an improved creep and shrinkage prediction model. It helps the design of prestressed concrete segmentally erected box girders as well as other creep-sensitive structures, such as cable stayed bridges with concrete pylons and steel or concrete beams, super tall buildings, large-span roofs, nuclear reactor vessels and containments, etc.

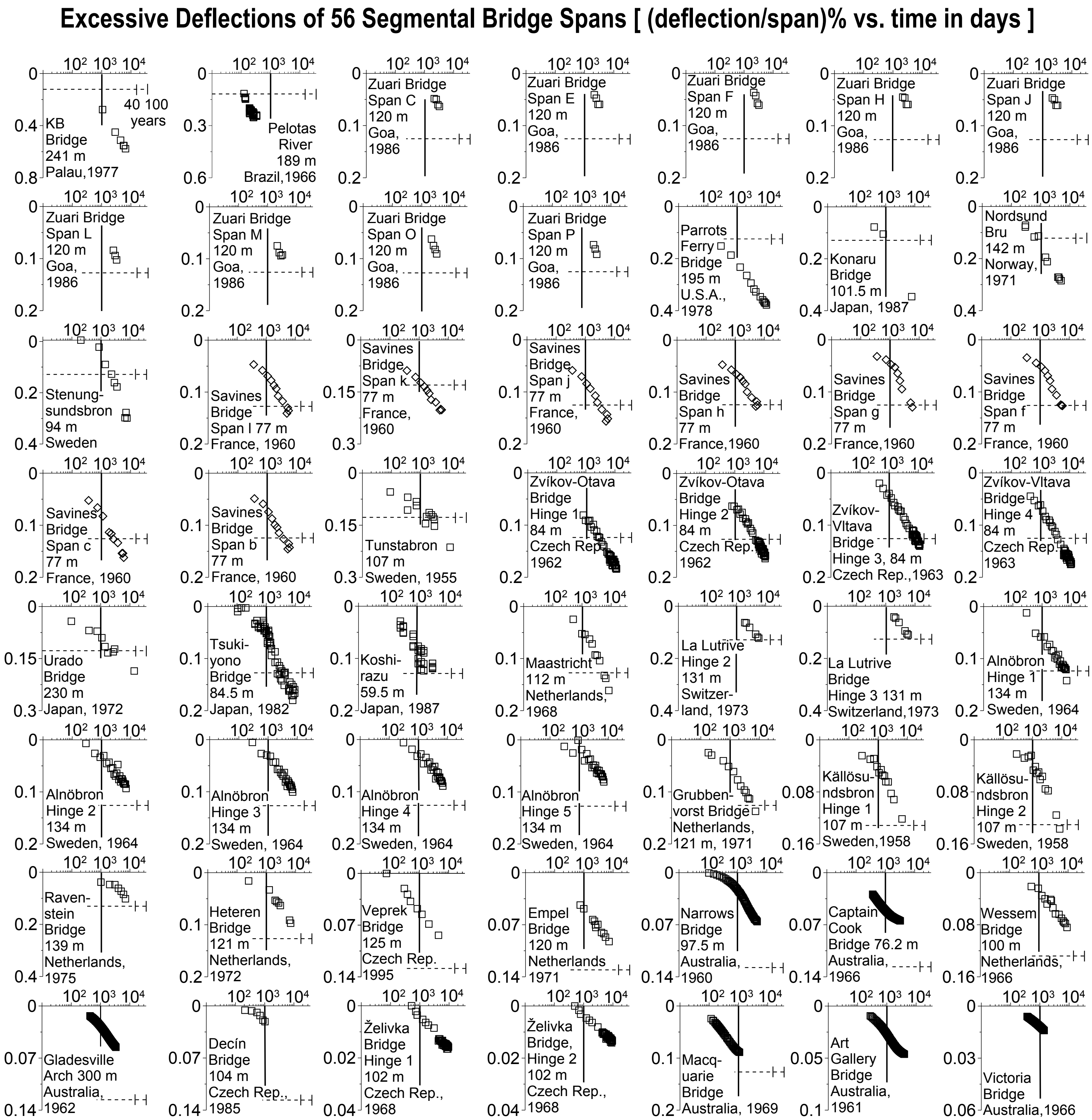

Fig. 2 Histories of excessive deflections of 56 large bridge spans (currently we have 69 examples). The horizontal dashed lines mark the excessive deflection limit according to AASHTO.

Task 2. Further Extension and Improvement of ITI Creep and Shrinkage Database

The effort of improving the existing database was tied to the collection of the database on segmental bridge deflections, which has already been discussed under Task 1. As mentioned, a major enlargement of our ITI database, already of unprecedented scope, was achieved through collaboration with a JSCE committee in Japan. However, the data they gave us were not consistently presented, since the long-time compliance values were reduced by the initial compliance values defined in different ways by various investigators. We had to go into the detailed records made available to us, to determine what would have been the correct compliance for a fixed initial time such as 0.01 day, and add these values to the data from Japan. Another problem with the Japanese data was that the comparison values for the standardized reference age of 28 days were missing, and so these data had to be generated by interpolation.

This effort has been completed. The new combined ITI-JSCE database is nearly ready (to be submitted to the AIC Materials Journal). It will be posted our website, and made available to the RILEM TC-MDC and to the ACI-209 committee.

Task 3. Viscoplastic Model for Prestressing Steel Relaxation at Variable Strain and Variable Temperature

The analysis of the bridge in Palau and four Japanese bridges revealed that excessive prestress losses, especially those due concrete creep and shrinkage and to steel relaxation, contribute greatly to excessive deflections and the consequent cracking. The bridge in Palau was unique in that some of the tendons were sacrificed before the retrofit in order to measure the stress in these tendons. The result was startling—an average prestress loss of 50%! Similar prestress losses likely occurred in all the other bridges studied, although they were not measured (or not reported). Calculations further showed that that the strains in tendons could not have been constant, as assumed in the classical steel relaxation formula, but must have varied significantly in time.

The current practice of estimating prestress loss uses vendor supplied data from short-time (typically 1000 hour tests) steel relaxation tests made in the factory. These tests are conducted at constant strain (and room temperature), and the relaxation loss for constant strain (and room temperature) is then used in the bridge analysis. It was thought that the effect of varying strain was not significant, but now we have a proof to the contrary.

Another major problem is that the loss is estimated for constant room temperature, while temperature can vary significantly. E.g., in box girders, many prestressing tendons are placed in the top slab. Since, in hotter countries, the sun can heat the pavement surface to as much as 60 ^{o}C, the top slab tendons can get periodically heated to about 40^{o}C for about 6 hours daily. We found that, according to the activation energy of steel, this period temperature increase can cause a 4-fold acceleration of the stress relaxation rate [10]. This conclusion is supported by test data from nuclear engineering literature A 30^{o}C temperature can be reached almost anywhere, and it suffices for a 2-fold acceleration.

A general constitutive (stress-strain-temperature) relation for the prestressing steel, in the form of an ordinary nonlinear differential equation in time, has been developed [10]. The main challenge was that nearly all the data on the prestressing steel relaxation are for constant strain. We could find only one limited test at step-wise changes of strain (Fig. 2). This would normally lead to non-uniqueness. However, this problem of non-uniqueness was overcome by invoking the following restrictions [10]:

1) In the nuclear engineering literature, there are tests of prestressing steel relaxation at changes of temperature which were not considered for bridges and buildings (Fig. 2). Due to thermal dilatation, the change of temperature causes changes of strain, and it is a matter of simple calculations to sort out the temperature effect on the flow rate [10].

2) It is known from extensive mechanical engineering literature that the constitutive law of creep of metals is a viscoplastic constitutive law with an Arrhenius type thermal prefactor characterized by atomistic activation energy. This greatly restricts the admissible form of the constitutive relation [10].

The steel relaxation data from various papers were compiled and computerized.The integral of the viscoplastic constitutive equation was programmed and was then fitted to the aggregate of these data, using nonlinear least-square optimization based on the Levenberg-Marquardt optimization algorithm. This exercise has lead to a superior model for steel relaxation, based on a sound and well proven theory of viscoplasticity [10]. This new model also provides a much better extrapolation to 100^+ years than the existing simplistic and purely empirical approach.

Task 4. Improvement of AAEM Method (ACI-209 Recommendation) for Multi-Decade Creep

In 1982, ACI-Committee 209 (and later also the European CEB code) adopted for simplified approximate structural creep analysis the so-called age-adjusted effective modulus method (AAEM), originally developed at Northwestern (Bažant 1972). This method allows an approximate quasi-elastic analysis of creep effects (deflections, stress redistribution, steel relaxation, creep buckling), suitable for structures of medium creep sensitivity. It means that commercial elastic finite element programs can be used. This method requires prior estimation of the relaxation function of concrete.

However, after the evidence from the KB Bridge in Palau and other bridges came to light, it turned out that the original formula for prior estimation of the relaxation function had a significant error in the case of multi-decade creep of concrete and that, for very long times, it could violate some thermodynamic restrictions. These violations included a recovery reversal (with a change of strain rate sign) and a change of stress sign during relaxation.

The theory for the AAEM method was modified so as to guarantee fulfillment of these thermodynamic condition even for multi-decade creep. Asymptotic conditions were enforced for this purpose and an asymptotic matching technique was employed. This resulted into an improved formula for the age-adjusted effective modulus, applicable to 100^+ years. The result has been submitted to ACI Committee 209, and also to the RILEM TC-MDC, and in press in JEM-ASCE [10a].

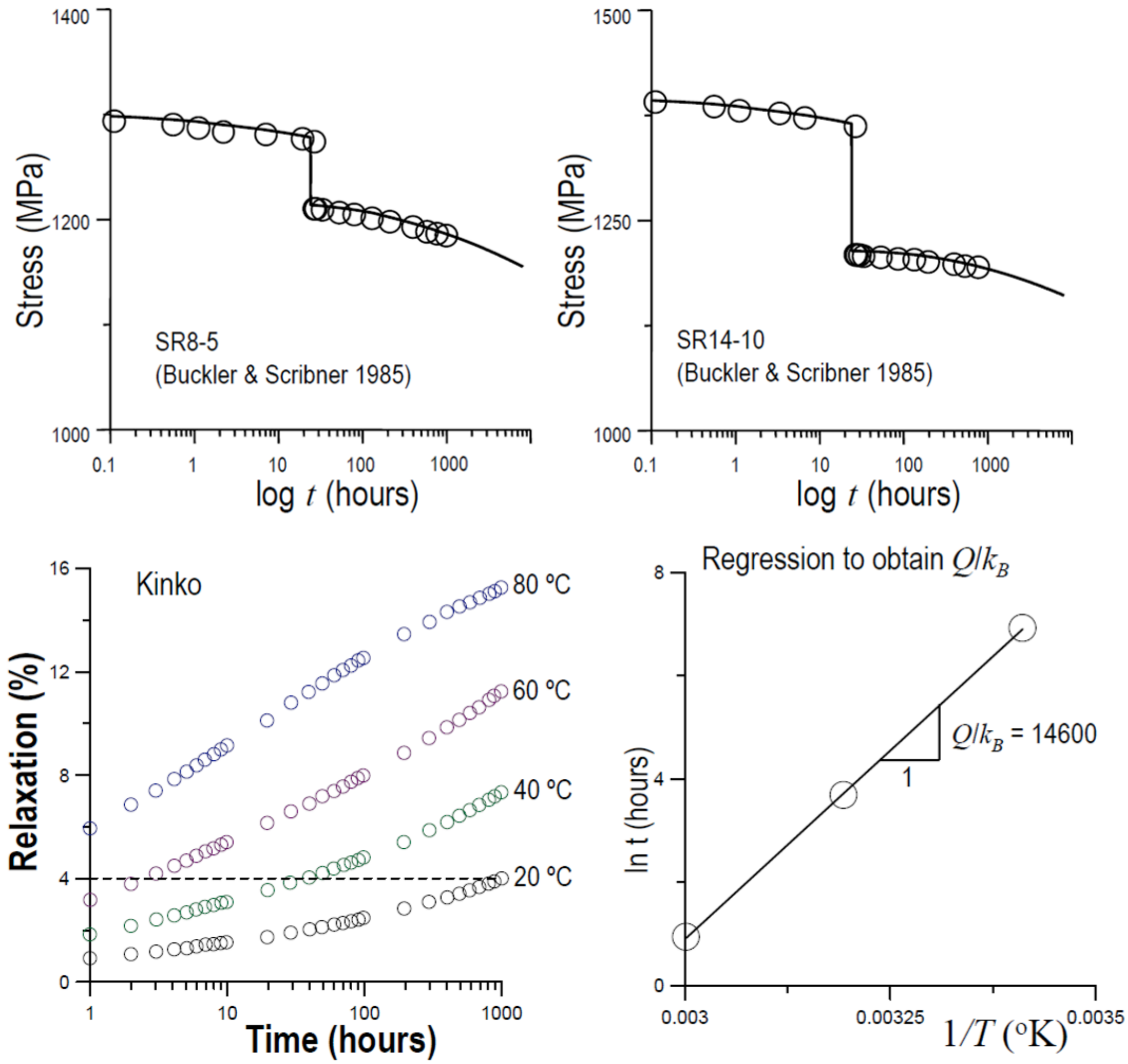

Fig. 3. Relaxation of prestressing steel at various temperatures and under step-wise change of strain, fitted by the new steel relaxation model.

Task 5. Promoting a New Direction of Standardization of Creep Analysis in ACI Committee 209

Building on Task 1, the PI began working in ACI Committee 209 in collaboration with a newly formed subcommittee on “Rate-type computer prediction of creep and shrinkage effects”. Thanks to the arrival of several young new members, the atmosphere in that committee become more open-minded because two influential and vocal defenders of the old methods retired, and because the weight of the evidence from the bridge in Palau and 69 other bridges became impossible to ignore.

This subcommittee is charged with developing a more realistic standardized method of finite element step-by-step structural creep analysis based on a rate-type model. A systemized computer algorithm for such a method has been developed [9] and has been submitted to this ACI 209 subcommittee for discussion.

Task 6. Safe Design of Sensitive Large Structures Based on Size Effect and Specified Tolerable Failure Probability

The probabilistic mechanics community has long discussed the probability of failure but a design procedure actually based on meeting a certain maximum tolerable failure probability has not materialized. One reason is that a Gaussian (or normal) distribution of structural strength has been assumed in developing the first and second-order reliability methods (FORM and SORM), and the corresponding reliability indices, i.e., the Cornell index and the Hasofer-Lind index. The problem was that it had never been proven that the cumulative distribution function (cdf) of structure strength is entirely Gaussian and sufficient for assessing failure probability $P_f < 10^{-6}$ (per lifetime). If the type of distribution, e.g. the Gaussian, is known, it suffices to know the mean and the coefficient of variation, and then the tail probability cutoff follows automatically. But a major problem arises if the distribution type is not known and varies with the structure size and geometry. This occurs for quasibrittle materials, concrete in particular.

The failure probability of $P_f = 10^{-6}$ is the maximum considered by reliability experts to be tolerable for the design of all engineering structures, including bridges, buildings, ships, commercial aircraft, etc. It is the value for which engineers are not appreciably increasing the risks to which people are inevitably and willingly exposed, such as automobile crashes, sports accidents, lightning strikes, hurricanes and tornados, earthquakes, etc.

Recent worldwide failure statistics collected by Melchers and by the Nordic Concrete Committee showed that, if the man-made causes such as negligence, sabotage, terrorism, poor quality control and design blunders are not counted, this tolerable maximum is generally met by normal size concrete structures. But these statistics also show that very large structures have been failing with the frequency 10^{-3}, which is intolerable.

The research funded by both this grant and NSF showed that the strength distribution of quasibrittle structures that fail at the macro-crack initiation from one representative volume element (RVE) can be statistically modeled as a finite chain of RVEs. Further it showed that, based on atomistic fracture mechanics and a statistical multi-scale transition model, the strength distribution of each RVE can be approximately described by a Gaussian (normal) distribution onto which a Weibull tail is grafted at the far-left at a point of probability of about 0.001. This new model implies that the strength distribution of quasibrittle structures must depend on the structure size, varying from the Gaussian distribution modified by a far-left Weibull tail for small-size structures to the purely Weibull distribution for large-size structures. Compared to the classical Weibullian strength distribution, which is limited to perfectly brittle structures, the grafted Weibull-Gaussian distribution makes the calculation of strength distribution of quasibrittle structures much more complicated.

The research led to the formulation of an approximate closed-form expression for the strength distribution using a series expansion of the grafted Weibull-Gaussian distribution [16]. Numerical examples, including the simple three-point and four-point bend beams and a bridge beam have been used to validate and verify this approximation. A nonlocal numerical method to calculate the effect of stress distribution on the quasibrittle failure probability has been devised [8].

Note the enormous consequences for the required safety (or understrength) factors. In the central range the Gaussian and Weibull distributions of the same mean and coefficient of variation are hard to distinguish, but the point of $P_f = 10^{-6}$ is for Weibull distribution almost twice as far from the mean, in terms of standard deviations, as it is for the Gaussian (or normal) distribution. Based on this fact it was shown that the safety factors for quasibrittle structures, including concrete structures failing at macro-crack initiation, should significantly increase with structure size. The design code should not prescribe a certain fixed value of the safety factor. Rather the safety factor should be calculated as a function of the structure size and shape. Obviously, it still remains to be a political challenge to introduce this into the design code.

Task 7. Fracture Experiments to Clarify the Size Effect at Small-to-Large Crack Transition and Their Extension to Size Effect under Fatigue Loading

Although hundreds of concrete fracture tests were carried out prior to this grant, their evaluation was ambiguous because they had limited ranges of specimen size, initial notch depth and postpeak response, and referred to different concretes, different batches of concrete, different ages, different environmental conditions, different loading rates and test procedures, and different specimen types. An experimental investigation of unprecedented comprehensiveness, using specimens made from one batch of concrete, was carried out under this grant [13]. It included: 1) notched and unnotched beams tested at virtually the same age; 2) crack depths ranging from 0 to 30% of beam depth; 3) a broad size range (1 : 12.5); 4) tests in transition range between type 1 and type 2 size effects; 5) virtually complete postpeak softening data; 6) properly correlated loading rates; and 7) complete standard characterization of the concrete used. The tests achieved an unusually low scatter (coefficient of variation of errors 2% only) [11].

All specimens had to be from one batch of concrete, and thus the forms could not be used repeatedly, or else the ages of specimens at the time of testing would be different. Consequently, 128 molds had to be fabricated, which was rather expensive.

The fracture test results for notched and unnotched beams were evaluated to clarify the size effects and fracture energy dissipation. The test results for beams with notches of various lengths agreed closely with Bazant's Type 2 effect law and yielded the value of the initial fracture energy G_f. Since nearly complete post-peak softening load-displacement curves were obtained, the total energy dissipation by fracture could be accurately evaluated and then used to determine the RILEM total fracture energy G_F [12]. For the present concrete, the ratio G_F/G_f was found to be approximately 2. The transition between the Type 1 and 2 size effects was determined and was found to be very different from that assumed in Hu and Duan's boundary effect model, a competing model.

The test results [11] were then used to derive and calibrate a universal size-shape effect law (Fig. 4), which is a law that describes the dependence of nominal strength of specimen or structure on both the structure size and the crack (or notch) length, over the entire range of interest, and exhibits the correct small-size and large-size asymptotic properties as required by the cohesive crack model (or crack band model) [13]. The main difficulty has been the transition of crack length from zero, in which case the size effect is of Type 1, to deep cracks (or notches), in which case the size effect is of Type 2 and is fundamentally different from Type 1, with different asymptotes. In this transition, the problem is not linearizable because the notch is not much larger than the fracture process zone. In contrast to previous

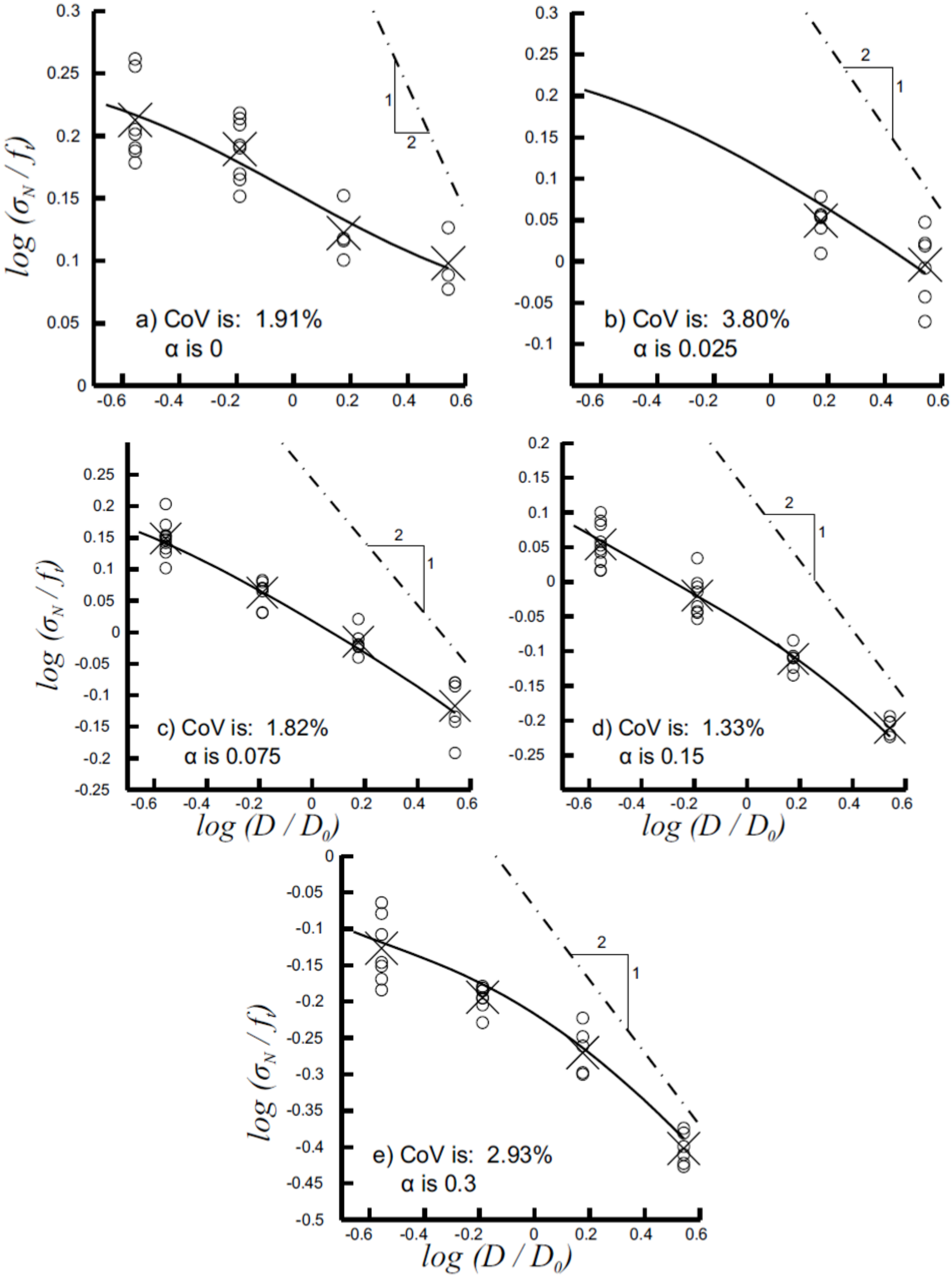

Fig. 4 New universal size-shape effect law and its comparison with Northwestern University tests.

attempts, the size effect for a zero notch and for the transitional range has been characterized in terms of the strain gradient at the specimen surface, which is the main variable determining the degree of stress distribution by the boundary layer of cracking. The new universal law is shown to fit the comprehensive data quite well, with the coefficient of variation of only 2.3 %.

The Type 1—Type 2 transition was one important remaining gaps in the quasibrittle size effect theory. It must also be understood for the formulation of boundary conditions of nonlocal damage models which capture the size effect in finite element analysis. This transition must also be understood to formulate the size effect specifications for shear and torsional failures of reinforced concrete beams with various degrees of reinforcement.

It may be emphasized that meeting mesh-insensitive finite element analysis of distributed fracturing and size effect, free of spurious localization problems, requires a nonlocal approach in which the fracturing strain increment at a continuum point is a function not of the total strain increment at that point but of the nonlocal increment obtained by averaging over the representative volume element of the material. Recently it transpired that problems arise near the boundaries where the theoretical averaging zone protrudes outside the body, and different adjustments yield very different results. In this study, a new idea was pursued: Separate a boundary layer of the structure, in which the nonlocal averaging is not carried out. Instead, the stress in this boundary layer, whose thickness is the minimum possible for a continuum model (only about two aggregate sizes), was simply calculated from the average strain across the layer [8].

Aside from completing the tests of monotonic fracture, the test program was further expanded to include tests under cyclic (pulsating, fatigue) loading, for which another set of specimens was cast. It need not be elaborated upon that the fatigue loading is particularly important for bridges, and for the medium spans (60 – 100 m) more than for large spans (up to 250 m) which are dominated by self-weight effects. The important information expected from these tests, yet to be completed, is the dependence of the (Paris type) power law for crack growth rate on structure size and the corresponding modification of the size effect in presence of fatigue loading. The crack length in fatigue crack growth was determined using the so called "CMOD-compliance" method, previously validated at Northwestern.

The concrete specimens that have been prepared (Fig. 5) have the size range of 1:12.5, which is the largest size range ever to be used in a larger series of fracture tests. It offers the advantage of minimizing the uncertainty in size effect due to data scatter. Additional specimens will also be prepared to experimentally determine the crack length using the so called "CMOD-compliance" method, which has already been validated at Northwestern for use in concrete specimens.

To minimize the effects of material randomness, all the beams have not only been cast from the same batch of concrete but also subjected to the same curing and preparation procedures. The ready-mix concrete was ordered and delivered to Northwestern University from Ozinga Bros., Inc. A team of about a dozen students moved the concrete from the truck spout and placed it as fast as possible into 128 molds of different sizes. The specimens were cast horizontally. The concrete was then vibrated to remove excess air voids, and excess material was be removed. Once cast, the beams remained in place, covered by a plastic sheet to prevent evaporation. After 24 hours, the beams were demolded and placed in an environmentally controlled room and cured at 100% humidity. Additionally, burlap was placed around all the beams to ensure keeping them wet. It was essential that the strength and

Table 1. Basic parameters of fracture tests carried out

Qty	Depth (mm)	Length (mm)	Thick (mm)	Alpha	Notch Depth (mm)	Notes
7	40	96	40	0	0	cyclic
7	40	96	40	0.3	12	cyclic
2	40	96	40	-	-	Compliance
4	40	96	40	0.3	12	Monotonic
6	93	223.2	40	0	0	cyclic
6	93	223.2	40	0.3	27.9	cyclic
2	93	223.2	40	-	-	Compliance
4	93	223.2	40	0.3	27.9	Monotonic
5	215	516	40	0	0	cyclic
5	215	516	40	0.3	64.5	cyclic
2	215	516	40	-	-	Compliance
4	215	516	40	0.3	64.5	Monotonic
5	500	1200	40	0	0	cyclic
5	500	1200	40	0.3	150	cyclic
2	500	1200	40	-	-	Compliance
4	500	1200	40	0.3	150	Monotonic
0	152.4	365.76	152.4	0	0	ASTM

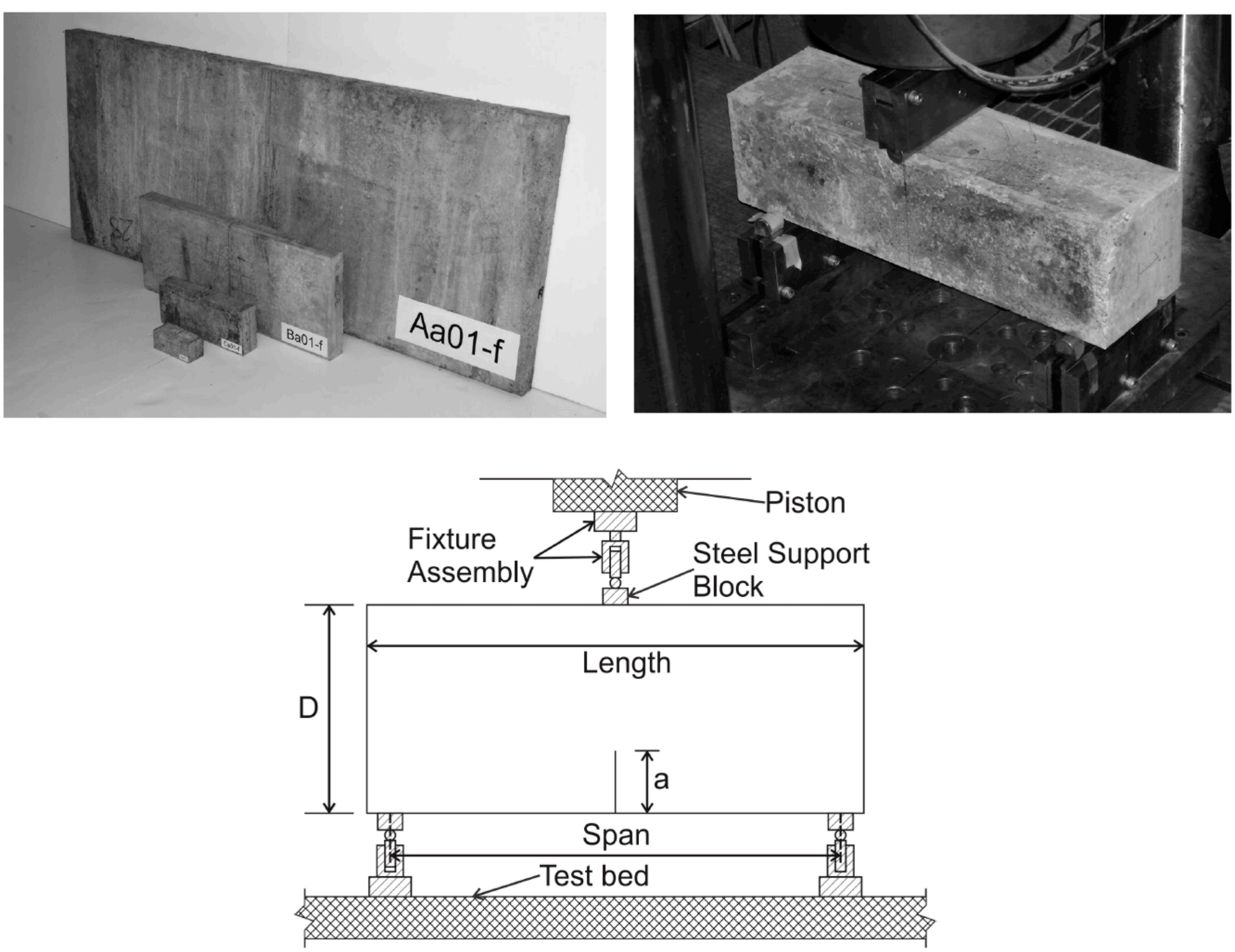

Fig. 5. Photos of fracture specimens used and load configuration.

compliance of all the beams would be the same at the time of testing, so that the test results would not be adversely affected by differences in the age of concrete. Therefore, after curing, the beams were moved to the ambient environment for a time period sufficient for the drying to stop the cement hydration before the testing. The notches were cut with a diamond band saw. Crack mouth opening displacement (CMOD) gauges were used to control the tests.

Task 8. Design Code Improvements: Size Effect in Shear, Torsional and Punching Failures of RC Beams and Slabs

The size effect in shear failure in RC beams without stirrups was the subject of a proposal of ACI Committee 446, Fracture Mechanics, for complete revision of Chapter 11 of ACI Standard 318, which was unanimously approved by ACI Committee 446, Fracture Mechanics and was subsequently submitted to the code committee ACI-318. A paper justifying the proposal in detail, both be theory and by extensive experiments was also published in ACI Structural Journal. ACI-318 referred this proposal for appraisal to ACI Committee 445, Shear and Torsion, which has not yet debated it. In a paper in press in JEM-ASCE, finished during the last year of investigation, it was shown that the inclusion of stirrups does not eliminate the size effect, which was the (wishful) thinking in ACI, but merely mitigates the size effect, pushing it into a larger size range. To introduce the size effect with stirrups into the design code will, of course, be an uphill political fight. On the other hand, progressive design firms increasingly conduct design checks that go beyond the code and are based on recent research results. If such checks are not made, the penalty will be that the failure probability of design will be much higher than 10^{-6}, but no design code has yet introduced an estimation of failure probabilities.

Since the promised enlargement of ACI-445 database on torsion and punching has lagged. This made it pointless to engage in statistical comparisons of the theory of size effect in torsion with the test data. So, this work is still in progress and will be complemented once the ACI Committee 445 completes the database.on torsion. A finite element program for torsional failure has also been developed and will be calibrated by the database once available. NSF funding will be sought for that purpose.

For the case of size effect in the punching shear failure of reinforced concrete slabs, methodical preparations were made during the last year of investigation. It is planned to prepare the initial finite element investigation of punching fracture and compare it to test data, hopefully in cooperation with the ACI committee 445. This problem is complicated by in-plane confining stress generated by the transverse expansion of the damage layer in punching shear fracture, which means that frictional slip must also play a role in the size effect in this mode of failure.

In collaboration with Prof. G. Zi of Korea University in Seoul, the size effect on the tensile strength of concrete has been investigated, too – both theoretically and experimentally, using circular plates failing under equi-biaxial tension. Tests of tensile strength under uniaxial tension were carried out for comparison, using four-point bend beams. For measuring the biaxial tensile strength, the ASTM C 1550 test and the biaxial flexure test have been examined. To study the size effect, unreinforced geometrically circular plates of three different sizes were tested, with 13 specimens per size. The size effect on the equi-biaxial tensile strength was found to be stronger than it is on the uniaxial tensile strength, and to exhibit the characteristics of the deterministic type size effect. The source of the size effect and its approximate law were clarified by a simplified analysis of the energy released by a crack of parabolic front, growing along the diameter from the tensile face across the plate thickness.

Task 9. Website Creep Design Aid for Predicting Creep and Shrinkage with Some Structural Effects

To facilitate the calculation of creep and shrinkage properties needed for analyzing the creep and shrinkage effects in structures, a open-source creep design aid program has been developed and is made freely available on a website [23]. The program is based on model B3, but can be easily adapted to other creep and shrinkage prediction models. Based on the given strength and the main characteristics of the given concrete, the program calculates, plots and tabulates the compliance function, relaxation function, creep coefficient, aging coefficient, and creep rate function. For ease of use, there is a user-friendly environment of the graphical user interfaces (GUIs).

The program also uses Latin hypercube sampling to calculate 95% or 90% and 85% confidence limits of the response curves from given coefficients variations of input data. Further it performs updating of long-term prediction based on given short-time test data, using either linear regression or Bayesian analysis.

Task 10. Activities to Improve the Standardized Fracture Test and Design Methods of ACI-446, ASTM-C09 and RILEM

The PI has had considerable success with the applications of his work on the size effect and on creep in various commercial computer programs (ATENA, SBETA, DIANA, OOFEM) and defense codes (EPIC, PRONTO), and also in the international standard recommendations of RILEM (model B3, the size effect method of testing the fracture energy, has been approved as international RILEM Recommendation). However, applications in the design code proved to be politically difficult and frustrating, and only partial success has been achieved by the PI. The success consists in 1) the inclusion of model B3 in the ACI-209 Creep Guide 2008; 2) the introduction of the first ever restrictions guarding against the size effect into the ACI-Standard 318, as limited and inaccurate these restrictions have been; 3) inclusion in ACI 446 report of a chapter on the size effect method for testing the fracture energy G_f of concrete, and of another chapter on the non-uniqueness of other methods that ignore testing at different specimen sizes. Item 3, however, did not suffice for acceptance by ASTM Committee C09, and further persuasion will be needed.

As member of C09, the PI will continue to argue for inclusion of the size effect correction in the flexural strength test standard, and advocate a new standard for fracture energy testing. As member of ACI-209 he will push for 1) a better standardized method of testing the long-term creep and shrinkage, 2) for a new guide recommending the rate-type method based on the solidification theory, 3) for a new recommendation on the creep and shrinkage prediction model based on an unbiased statistical comparisons relying both on the measured creep deflection data and the laboratory database, and 4) for introduction of the size effect into the code provisions for torsion and for punching shear.

Task 11. Activities to Achieve a Society Ethics Code and/or a Federal Law Prohibiting the Concealment of Technical Data from Structural Damages and Failures

The data on the 1996 failure of the record-setting bridge in Palau were sealed in 1977 in perpetuity. The PI’s effort led in November 2007 to a resolution of the Structural Engineers World Congress

(SEWC) which condemned the sealing of data from failures as a violation of engineering ethics. Two months later (in 2009) the data were released to Northwestern University. Analysis of these data revealed problems with the design code and design practice which would not have come to light if the data remained sealed. Subsequent search led to a wake-up call: 69 excessively deflecting large segmental bridges have so far been identified and probably many more exist.

Based on these revelations, the PI campaigned in the Civil Engineering Section of the National Academy of Engineering for a resolution similar to that passed by the SEWC. Despite vehement opposition of academy members with forensic activities, the effort eventually succeeded, though only after a two-year debate. However, similar proposals of the PI made in ASCE and in ACI lie in limbo. Based on SEWC resolution, the PI proposed to NAS and NAS to push jointly for enactment of a federal law banning data sealing from major civil engineering disasters (such a law already exists in commercial aviation). Currently this matter is still in the hands of the NAS-NAE joint Committee on Science, Technology and Law.

Although partial success has already been achieved, doubtless much more effort in persuasion and politics in the engineering and scientific societies will be need. Without the support of this grant, a good start would not taken place. The PI will seek NSF support to continue these activities.

Publications During 5 Years of Investigation

(funded fully or partly by this grant)

(*each can be downloaded from:* www.civil.northwestern.edu/people/Bazant.html)

Refereed Journal Articles:

Note: Only the papers referenced in the text are numbered. .They represent the main papers.

[1] Bažant, Z.P., Yu, Q., Li, G.-H., Klein, G.J., and Kristek, V. (2010), "Excessive deflections of record-span prestressed box girder: Lessons learned from the collapse of the Koror-Babeldaob Bridge in Palau." ACI Concrete International 32 (6), June, 44-52.

[2] Yu, Qiang, Bažant, Z.P. (2011). "Can stirrups suppress size effect on shear strength of RC beams?" ASCE J. of Engrg. Mech. 137 (5), 607--617.

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[5] Bažant, Z.P., Yu, Qiang, and Li, Guang-Hua (2012). "Excessive long-time deflections of prestressed box girders: I.~Record-span bridge in Palau and other paradigms." ASCE J. of Struct. Eng. 138 (6), 676--686.

[6] Bažant, Z.P., Yu, Qiang, and Li, Guang-Hua (2012). "Excessive long-time deflections of collapsed prestressed box girder: II.~Numerical analysis and lessons learned." ASCE J. of Structural Engrg. 138 (6), 687--696.

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[8] Le, Jia-Liang, Elias, J., and Bažant, Z.P. (2012). "Computation of probability distribution of strength of quasibrittle structures failing at macrocrack initiation." ASCE J. of Engrg. Mechanics 138 (7), 888--899.

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[10a] Bažant, Z.P., and Hubler, M.H. (2012). "Long-term approximate relaxation function for concrete." ASCE J. of Engrg. Mech., in press.

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[12] Hoover, C.G., and Bažant, Z.P. "Comprehensive concrete fracture tests: Size effects of types 1 \& 2, crack length effect and postpeak." ACI Mater. J., submitted to.

[13] Hoover, C.G., and Bažant, Z.P. "Universal size-shape effect law based on comprehensive concrete fracture tests." ASCE J. of Engrg.Mechanics, submitted to.

[14] Caner, F.C., and Bažant, Z.P. "Microplane Model M7 for Plain Concrete: I. Formulation." ASCE J. of Engrg. Mechanics, submitted to.

[15] Caner, F.C., and Bažant, Z.P. "Microplane Model M7 for Plain Concrete: II. Calibration and Verification." ASCE J. of Engrg. Mechanics, submitted to.

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PROCEEDINGS PAPERS:

Bažant, Z.P., and Le, Jia-Liang (2010). "Statistical aspects of quasibrittle size effect and lifetime, with consequences for safety and durability of large structures." in Fracture Mechanics of Concrete and Concrete Structures--Recent Advances in Fracture Mechanics of Concrete (Proc., FraMCoS-7, 7th Int. Conf. held in Jeju, Korea, plenary lecture), B.-H. Oh, ed., publ. by Korea Concrete Institute, Seoul, pp. 1--8.

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Special Issues in Honor of Bažant

C.K.Y. Leung and K. Willam, Guest Editors (2007), Special Issue dedicated to Z.P. Bažant, Engineering Fracture Mechanics 74 (1-2), pp. 1-280 (20 papers).

Appendix II: Lectures on, or Related to, ITI Funded Project
During 2007-2009

Nano-mechanics based assessment of failure risk and lifetime of quasibrittle structures at different scales, Keynote Address. **Plenary opening lecture**, 3rd Int. Conf. on Struct. Engrg., Mech. and Computations (SEMC), Univ. of Cape Town, Sept. 10, 2007.

Consequences of ignoring or misjudging the size effect in concrete design codes and practice. **Plenary opening lecture**. 1st Annual Convention of Taiwan Concrete Institute (TCI), Nov. 2, 2007, Taipei, Taiwan.

Consequences of ignoring or mis-judging the size effect in concrete design codes and practice. **Plenary lecture**. 3rd Structural Engineers World Congress, Nov. 5, 2007, Grand Ashok,Hotel, Bangalore, India.

Probabilistic mechanics of scaling of strength and lifetime of quasibrittle structures: nano to macro. IISc Mathematics Initiative Lecture, Nov. 7, 2008, Department of Mathematics, Indian Institute of Science, Bangalore, India.

Size effect of probability of quasibrittle failure and lifetime: from atomistic to structural scale. **Plenary opening lecture**, Int. Conf. on "Physical Aspects of Fracture Scaling and Size Effects", org. by ETH Zurich, March 10, 2008, Monte Verita, Ascona, Switzerland.

Computing quasibrittle failure probability: from nano to macro. **Semi-Plenary Lecture**, 8th World Congress on Computational Mechanics (WCCM8), July 2, 2008, Venice-Lido, Italy.

Comparison of prediction models and design approaches for creep and shrinkage of concrete, ACI Fall Convention, Fajardo, Puerto Rico, Oct. 15, 2007.

Size effect on strength and lifetime distributions of quasibrittle structures, implied by interatomic bond break activation (co-author J.-L. Le). Stein Sture Symposium on Geomechanics,

Inaugural Int. Conf. of the Engineering Mechanics Institute (em08) ASCE, May 19, 2008, University of Minnesota, Minneapolis.

Microplane modeling of damage and fracturing in particulate and fiber composites and bio-materials. Opening lecture of Symp. on Advances in Computational Mechanics in Honor of Prof. Maier, 8th World Congress on Computational Mechanics (WCCM8), June 30, 2008, Venice-Lido, Italy.

Collapse of World Trade Center Towers: What did and did not cause it? National Chen-Kung University (NCKU), Oct. 30, 2007, Tainan, Taiwan.

Mechanics of progressive collapse: What did and did not doom World Trade Center, and what we can learn. Dipartimento di Ingegneria Strutturale, Politecnico di Milano, Nov. 12, 2007, Milan, Italy.

Microplane modeling of damage or fracture, and multiscale concepts. Dipartimento di Ingegneria Strutturale, Politecnico di Milano, Nov. 13, 2007, Milan, Italy.

Nano-mechanics based assessment of failure risk and lifetime of quasibrittle structures at different scales. Dipartimento di Ingegneria Strutturale, Politecnico di Milano, Nov. 13, 2007, Milan, Italy.

Multiscale, miroplane and lattice models: advantages, limitations and localization problems. Struct. Eng. and Struct.

Mech. Seminar, University of Colorado, Jan. 15, 2008, Boulder, Colorado.

Failure risk and lifetime of quasibrittle structures: from atomistic to structural scale. Struct. Engrg. Seminar Series, University of Illinois Urbana-Champaign (UIUC), Jan. 28, 2008, Urbana, Illinois.

Failure risk and lifetime of quasibrittle structures: from atomistic to structural scale. MMMC (Mech., Modeling, Experimenation, Computation) Seminar Series, Dept. of Mechanical Engrg., M.I.T., Feb. 19, 2008, Boston, MA.

Failure risk and lifetime of quasibrittle structures: from atomistic to structural scale. ETH, March 7, 2008, Zurich-Honggerberg, Switzerland.

Failure risk and lifetime of quasibrittle structures: from atomistic to structural scale. ESPCI (Ecole superieure de physique and de chimie industrielle), LPCT (Laboratoire de physique et chimie theorique), March 21, 2008, Paris 5.

Computing quasibrittle failure probability: from nano to macro. Croatian Assoc. for Mech., University of Rijeka, June 27, 2008, Rijeka, Croatia.

Statistical mechanics of reliability of brittle and quasibrittle structures and size dependence of understrength safety factors (presented by co-author S.-D. Pang). 10th INt. Conf. on Applications of Statistics and Probability in Civil Engrg. (ICASP10), Aug. 2007, Tokyo, Japan.\

Dependence of size effect law for quasibrittle materials on loading duration (presented by co-author Jia-Liang Le), 10th Pan American Congress of Applied Mechanics, Jan. 2008, Cancun, Mexico.

Mesomechanical multiscale elastic-fracturing model for braided composites (co-authors: F. Caner, C. Hoover). 49th AIAA/ASME/ASCE Structures, Structural Dynamics and Materials Conf., April 8, 2008, Schaumburg, Illinois.

Size effect on strength of hybrid metal-composite joints (co-authors, F. Caner, J.-L. Le, Q. Yu). 49th AIAA/ASME/ASCE Structures, Structural Dynamics and Materials Conf., April 9, 2008, Schaumburg, IL.

Atomistically based prediction of size effect on strength and lifetime of composites and other quasibrittle structures (presented by co-author Jia-Lian Le). 49th AIAA/ASME/ASCE Structures, Structural Dynamics and Materials Conf., April 10, 2008, Schaumburg, Illinois.

Unbiased statistical comparison of creep and shrinkage prediction models. Meeting of ACI Committee 209, Creep and Shrinkage, ACI Spring Convention, March 31, 2008, Los Angeles.

Problems with nonstandard regression statistics in database evaluations of design equations. Meeting of ACI Committee 348, Structural Safety, ACI Spring Convention, March 31, 2008, Los Angeles.

Size effect in shear of R.C. beams predicted by fracture mechanics. ACI Spring Convention, April 1, 2008, Los Angeles.

Size effect in textile composites: elasticity and fracture of braided composites (co-author A. Waas). ACC (Automobile Composites Consortium) Energy Management Meeting, USCAR Headquarters, May 8, 2008, Southfield, Michigan.

Consequences of fracture mechanics for size effect, crack spacing, and crack width in concrete pavements. 6th RILEM Int. Conf. on Cracking in Pavements, Holiday Inn, Chicago.

A. General or Plenary Keynote Lectures at Conferences & Distinguished or Endowed Lectures

Size effect on strength and lifetime distributions of Quasibrittle structures implied by interatomic bond break activation (with J.-L. Le and M.Z. Bažant), plenary lecture, 17th Eur. Conf. on Fracture, Brno, Czech Rep., Sept. 3, 2008.

Prediction of creep and shrinkage and their effects in concrete structures: critical appraisal (with G.-H. Li and Q. Yu), 8th Int. Conf. on Creep, Shrinkage and Durability of Concrete and Concrete Structures (CONCREEP-8), Ise-Shima, Japan, Sept. 30, 2008.

Quasibrittle fracture and its scaling: problems, progress, practice (Nadai Medal Lecture), ASME Intern. Mechanical Engrg. Congress, Boston, Nov. 4, 2008.

Size and risk: scaling of quasibrittle structure strength and lifetime based on atomistic fracture mechanics, Inaugural Lecture, Spanish Royal Academy of Engrg., Madrid, March 24, 2009.

Collapse of record-span segmental box girder bridge in Palau and lessons from excessive long-time deflections, 2009 Richardson Lecture, Dept. of Civil and Env. Engrg., University of Colorado, Boulder, April 15, 2009.

Lessons from excessive long-time deflections and collapse of record-span segmental box girder bridge in Palau (plenary lecture), Korea Concrete Institute, Spring Convention, Busan, Korea, May 7, 2009.

Size and risk: scaling of quasibrittle structure strength and lifetime based on atomistic fracture mechanics, 2009 Distinguished Lecture, Civil and Env. Engrg. Dept., Univ. of California Los Angeles (UCLA), May 19, 2009.

Modeling of creep and hygrothermal deformations of concrete: Intriguing consequences of nanoporosity, Biot Lecture (plenary), 4th Biot Conference on Poromechanics, Columbia University, New York, June 8, 2009.

Black holes in probability tails: Challenge for safety analysis of quasibrittle structures (co-authors J.-L. Le and Jan Elias). Opening Plenary Lecture. 11th Int. Conf. on Computational Plasticity---Fundamentals and Applications (COMPLAS XI, an ECCOMAS Conf.), UPC, Barcelona, Sept. 7, 2011.

Computational challenges to cure a plague of multi-decade creep damage in concrete infrastructure (co-authors R. Wendner and M. Hubler), semi-plenary lecture, 10th World Congress of Computational Mechanics (WCCM), Sao Paulo, Brazil, July 11, 20121.

Excessive creep deflections of prestressed segmental bridges: A wake-up call for design codes and consequences of nano-porosity, CEAS Distinguished Lectures, College of Engrg. and Appl. Sci., University of Wisconsin, Milwaukee, Oct. 28, 2011.

Pervasiveness of concrete creep problems in structures: wake-up call for design codes and consequences of nano-porosity. CoE Distinguished Lecture, College of Engrg., University of Miami, Corral Gables, FL, Nov. 7, 2011.

Pervasiveness of concrete creep problems in structures: Wake-up call for design codes and consequences of nano-porosity. Honorary Professor Lecture, Southeast University, Nanjing, China.

Pervasiveness of concrete creep problems in structures: Wake-up call for design codes and consequences of nano-porosity. Honorary Professor Lecture, Xi'an Jiaotong University, Xi'an, China.

B. Invited Conference Lectures

Strength of quasi-brittle ceramics: Impossibility of finite Weibull threshold and statistical justification in nano-mechanics (with J.-L. Le, S.-D. Pang) Soc. of Engrg. Science 45th Annual Techn. Meeting (Eringen Medal Symp. honoring S. Suresh), Univ. of Illinois, Urbana, Oct. 13, 2008.

Plastic-fracturing transition of size effect (with Q. Yu, J.-L. Le, C.G. Hoover and F.C. Caner), 15th Int. Symp. on Plasticity and Its Current Applications, Jan. 4, 2009.

Atomistic fracture and nano-macro transition for strength and lifetime of quasibrittle structures, Sectional Keynote Lecture, 12th Int. Conf. on Fracture (ICF12), Ottawa, Canada, July 15, 2009.

Quasibrittle size effect: Problems and Progress, Sectional Keynote Lecture, 12th Int. Conf. on Fracture (ICF12), Ottawa, Canada, July 16, 2009.

Problems of boundary conditions in nonlocal and cohesive models for material damage and quasibrittle fracture. Sectional Keynote Lecture, CFRAC 11 (Computational Modeling of Fracture and Failure of Materials and Structures), UPC Barcelona, June 6, 2011.

Wake-up call for creep, myth about size effect and black holes in safety: What to improve in fib Model Code draft. Theme II keynote Lecture, fib Symposium Prague 2011 "Concrete Engineering for Excellence and Efficiency", Prague (Hotel Clarion), June 8, 2011.

Panel discussion on "Infractructure---Past, Present and Future", Dept. of Civil & Env. Engineering, Northwestern University, Apr. 29, 2011.

Microplane model M6f for concrete. Sectional Keynote Lecture, USNCCM-11 (11th U.S. Nat. Congr. of Computational Mechanics), Minneapolis (Hilton), July 25, 2011.

Correct work-conjugate stress and strain measures for accurate numerical modeling of finite deformation. Sectional Keynote Lecture, USNCCM-11 (11th U.S. Nat. Congr. of Computational Mechanics), Minneapolis (Hilton), July 27, 2011.

Mechanisms of sorption hysteresis and discrete disjoining pressure effects in nano-porous solids (co-author M.Z. Bazant), Prager Medal Symp. in honor of Prof. T.B. Belytschko, 48th Annual Tech. Conf. of the Society of Engrg. Science, Northwestern University, Oct. 12, 2011.

C. Invited Colloquium Lectures and Seminars at Universities and Laboratories

Multiscale, microplane and lattice models: advantages, limitations and localization problems, Tongji University (Civil Engrg. Dept.), Shanghai, Sept. 24, 2008.

Consequences of ignoring the size effect in concrete practice and design codes in shear, Shanghai Jiao Tong University, Sept. 26, 2008.

Prediction of concrete creep, shrinkage and their effects in structures: critical appraisal, Techn. Univ. Vienna (Institute for Materials and Structures), Nov. 24, 2008.

Size and risk: Scaling of quasibrittle structure strength and lifetime based on atomistic fracture mechanics, Univ. of Pennsylvania, Dept. of Mechanical Engrg. and Appl. Mech., Philadelphia, Feb. 19, 2009.

Failure risk and lifetime of quasibrittle composites: nano to macro, Northwestern University, Theor. and Appl. Mech. Seminar, Feb. 27, 2008.

Size and risk: Scaling of quasibrittle structure strength and lifetime based on atomistic fracture mechanics, University of Utah, Dept. of Materials Science and Engrg., Salt Lake City, March 4, 2009.

Lessons from excessive long-time deflection and collapse of record-span segmental box girder bridge in Palau, Instituto de Ciencias de la Construcci\'on Eduardo Torroja, Madrid, March 26, 2009.

Lessons from excessive long-time deflections and collapse of record-span segmental box girder bridge in Palau, Czech Technical University (CTU), Joint Lecture of CTU Institute of Mechanics and of Czech Society of Mechanics, Prague, March 30, 2009.

Scaling of quasibrittle structure strength and lifetime based on atomistic fracture mechanics, Seminar of Dept. of Materials and Engrg., Northwestern University, Evanston, IL, June 2, 2009.

Scaling of quasibrittle structure strength and lifetime based on atomistic fracture mechanics, GALCIT Colloquium, Graduate Aerospace Laboratories, California Institute of Technology, Pasadena, CA, June 5, 2009.

Probabilistic nano-mechanical theory of quasibrittle structure strength, crack growth, lifetime and fatigue. Department of Civil Engineering, Delft University of Technology, The Netherlands, June 14, 2011.

Excessive creep deflections of prestressed segmental bridges: A wake-up call for design codes and consequences for nano-porosity. Dept. of Civil Engineering, Technion, Haifa, Israel, Sept. 11, 2011.

Progress engendered by collapses of record setting structures: World Trade Center Towers, Malpasset Dam and KB Bridge in Palau, Dept. of Mechanical Engrg., Tel Aviv University, Tel Aviv, Israel, Sept. 14, 2011.

Theory of sorption hysteresis in nanoporous solids---snap-through instabilities. Special Seminar, Dept. of Civil Engrg., M.I.T., Cambridge, MA, Dec. 5, 2011.

Disjoining pressure and sorption hysteresis of adsorbate in nanoporous materials, Faculty-Faculty Seminar, Northwestern University, Jan. 3, 2012.

Pervasiveness of concrete creep problems in structures: Wake-up call for design codes and consequences of nano-porosity. College of Engineering Seminar, University of Akron, Akron, OH, March 21, 2012.

Excessive bridge deflections: Wake-up call for design codes. Infrastructure Technology Institute (ITI), Research Associates Meeting, Evanston, April 9, 2012.

Energy-inconsistent objective stress rates in ABAQUS, ANSYS, LS-DYNA and other FE Codes: Magnitude of errors and how to correct them. School of Engineering, Peking University, Beijing, May 10, 2012.

Probabilistic nano-mechanical theory of quasibrittle structure strength, lifetime and fatigue. Dept. of Engineering Mechanics, Tsinghua University, Beijing, May 11, 2012.

Wake-up call from collapse of world-record bridge: Pervasiveness of excessive creep deflections and misleading design codes. Dept. of Engineering Mechanics, Tsinghua University, Beijing, May 11, 2012.

Errors of ABAQUS, LS-DYNA, ANSYS and other commercial codes caused by using energy-inconsistent objective stress rates (co-authors J. Vorel and M. Gattu), NU 2012 Summer Workoshop on Computational Science and Engineering (in honor of Wing-Kam Liu's 60th birthday), Hilton Garden Inn, Evanston, IL, July 23, 2012.

D. Contributed Conference Papers

Size effect: What is the rationale and penalty for neglect, 17th Congress of IABSE, Chicago, Sept. 18, 2008.

Misprediction of long-time deflections of prestressed box girders: Causes, remedies and tendon layout effect (V. Kristek, L. Vrablik-presenter, Z.P. Bažant, G.-H. Li and Q. Yu), 8th Int. Conf. on Creep, Shrinkage and Durability of Concrete and Concrete Structures (CONCREEP-8), Ise-Shima, Japan, Oct. 1, 2008.

The problem of non-disclosure of technical data from major structural failures, presentation in the Civil Eng. Section Meeting, National Academy of Engrg. Annual Meeting, Oct. 6, 2008.

Analysis of causes of excessive long-time deflections of the prestressed box girder bridge in Palau, presentation to ACI-209 Committee meeting, ACI Spring Convention, San Antonio, TX, March 16, 2009.

Explanation of excessive long-time deflection of collapsed record-span box girder bridge in Palau, SEAOI Midwest Bridge Symposium, Chicago, April 23, 2009.

Size effect on strength and lifetime distributions of quasibrittle structures implied by atomistic fracture mechanics (with J.-L. Le and M.Z. Bažant), Joint ASCE-ASME-SES Conf. on Mechanics and Materials (Mech09), VPI, Blacksburg, VA, June 26, 2009.

Size effect on probability distributions of fatigue lifetime of quasibrittle structures (presented by co-author Jia-Liang Le). ICASP 11 (11th Int. Conf. on Applications of Statistics and Probability in Civil Engineering). ETH Zurich, August 3, 2011.

Microplane model M6f for fiber-reinforced concrete (presented by co-author F. Caner), 11th Int. Conf. on Computational Plasticity---Fundamentals and Applications (COMPLAS XI), UPC, Barcelona, Sept. 8, 2011.

Myth and reality of multiscale modeling of concrete and other quasi-brittle materials (presented by co-author G. Cusatis), 14th Intern. Symp. on Interaction of the Effects of Munitions with Structures, Renaissance Seattle Hotel, Seattle, Sept. 20, 2011.

Size effect on sandwich plates with imperfections caused by cohesive delamination fracture triggered by skin wrinkling (co-authors M. Gattu and P. Grassl), ASME Intern. Mechanical Engrg. Congress and Exp., Denver, Nov. 17, 2011.

Non-uniqueness in softening damage and cohesive fracture models for concrete or bone caused by ignoring the size effect, ASCE Structures Congress, Chicago, March 30, 2012.

Large sandwich panels for lightweight ship hulls: Buckling with fracture and size effect. Office of Naval Research (ONR) Review Meeting on ``Ship Hull Structures", Arlington, VA, May 15, 2012.

Size effect in bone fracture and its use to avoid non-uniqueness of cohesive stress-separation law (presented by co-author K.T. Kim), EMI/PMC (2012 Joint Conf. of Eng. Mech. Inst. and 11th Joint Specialty Conf. on Probab. Mechanics and Struct. Reliability), Univ. of Notre Dame, South Bend, IN, June 18, 2012.

Snap-through instabilities as a cause of sorption hysteresis and misfit disjoining pressure in hydrated cement and other nanoporous solids (co-authors M. Hubler and M.Z Bazant), ibid. June 18, 2012.

Corrections to ABAQUS, ANSYS, LS-DYNA and other FE Codes required by work-conjugacy and orthotropy effects in finite strain and stability analyses (co-authors M. Gattu and J. Vorel), ibid. June 18, 2012.

Uncertainty in creep and shrinkage prediction models for concrete (presented by co-author R. Wendner, co-author M. Hubler), ibid., June 19, 2012.

Computation of scale effects on structural safety of quasibrittle structures presented by co-author J.-L. Le, co-author Jan Elia s), ibid., June 20, 2012.

Symposia in Honor of Bažant

Pre-conference Workshop, and Symposium at ECCOMAS Thematic Conference on Mechanics of Heterogeneous Materials, honoring Bažant at his 70th birthday, Prague, June 24 and 26, 2007.

Asian Special Workshop on Concrete Technology in Honor of the 70th Birthday of Prof. Zdenek P. Bažant, chaired by Ta-Peng Chang and Jenn-Chuann Chern at TCI Annual Meeting, Taiwan National University, Nov. 2, 2008, Taipei, Taiwan.

Symposium in honor of Prof. Bažant's 70th birthday, Joint ASCE-ASME-SES Mechanics and Materials Conference (Mech09), VPI, Blacksburg, VA, June 25, 2009