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CIMNE And The Butterfly Effect

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Thoughts on the celebration of CIMNE 25th year got entwined in my mind with the unusual importance of seemingly uncorrelated events. An instance of the Butterfly Effect. As the King James' Bible warns: *"… but time and chance happenneth to them all."* My argument: If Ray Clough had not been born in Seattle, CIMNE might not exist. To back up the hypothesis, the fluttering butterfly will take us through Boeing, Berkeley and Swansea, stressing some early, player-driven, developments in computational mechanics. The path is abbreviated as the *BBS connection* in the sequel.

Three major pre-CIMNE players appear in this story: M. Jonathan (Jon) Turner, Ray W. Clough, and Olgierd (Olek) C. Zienkiewicz. Born in 1915, 1920 and 1921, respectively, they belong to the First Generation of the pioneers who created the Finite Element Method (FEM). Only Clough remains alive. Turner and Zienkiewicz passed away in 1995 and 2009, respectively. Other early contributors: Argyris, Fraeijs deVeubeke, Gallagher, Irons, Martin, Melosh, and Pian, are also gone.

The FEM Paella

The version of FEM universally used today in hundreds of computer programs is called the Direct Stiffness Method, or DSM. That was the brainchild of Jon Turner at Boeing. Its development started by 1952, about the time the first digital computers (built by Sperry Rand) appeared on the market. The baby "FEM paella" combines three main ingredients: variational mathematics (meat and vegetables), matrix structural analysis (rice), and the digital computer (fire). While the first two ingredients were available by 1950, the third one was missing. Without computers, FEM would be an uncooked dish. Original machines were vacuum-tube-driven monsters that cost over $20M each in current dollars, and required a dedicated staff of specialists to operate. In the early 1950s, only two organizations could afford that kind of money: government agencies (notably defense and intelligence, who do not eat paellas), and aerospace companies. No wonder that FEM evolved initially in aerospace.

Two well known paella types are *valenciana* and *de mariscos*. Likewise, baby FEM for structural mechanics grew up in two flavors: *displacement* and *force*. The duality reflects two formulations of structural engineering, systematized in the late XIX Century. Since the force method had been the favorite for hand use, most aerospace companies naturally bet on continuing dominance once it was computer implemented. Two companies, however, went against the grain and allocated resources to the displacement method. Those efforts were led by Turner at Boeing and Gallagher at Bell Aerospace.

By 1970 the DSM displacement-based version had won the battle. FEM was prominent beyond aerospace, had entered Civil and Mechanical Engineering, and overspilled beyond structures. This final success was driven by a sequence of technological and human events, as chronicled next.

Delta Wings

The realistic model-based simulation of delta wings for post-WW2 fast aircraft provided a crucial early test of the new capabilities promised by the advent of digital computers. Vibration and aeroelastic analyses were overarching project drivers. By comparison static analysis was of minor importance except for model validation benchmarks against load tests. Turner soon realized that the force method was handicapped in dynamics. No mystery there: inertial force is mass times acceleration, which require access to displacements. (The same observation applies to FEM stability analysis, which was developed during the 1960s.) Another major bottleneck of the force method was the automatic assembly of governing matrix equations for complex 3D systems: a programming nightmare. Turner solved both difficulties by developing the concept of *finite element discretization as a kinematic breakdown of the original structure*. For delta wings a combination of 3-node and 4-node membrane plates with 2-node spars (all of them in 3D space) proved sufficient. The initial efforts dealt with element development and testing, and spanned two years: 1952-53. Over this period, Turner's team had the onsite help of two rising-star, junior faculty: Clough and Martin, during the summer months of academic recess. Clough would eventually become the key player in "exporting" FEM to Civil Engineering, an event called here the Boeing-Berkeley (BB) connection.

Results of these activities appeared 3 years later in a seminal paper: *Stiffness and deflection analysis of complex structures*, *J. Aero. Sci.,* **23,** 1956. It boasts the most citations of the early (pre-1970) FEM literature. But the DSM description would not be finished until 1964, when the matrix assembly process (the dual of the structural breakdown) was carefully covered in a book chapter written by Turner, Martin and Weikel.

The BB Connection

Ray Clough was born and raised in Seattle. He became an avid mountaineer and skier: his name appears in the record books for difficult climbs and traversals. After studies interrupted by WW2, during which he served in the Air Force (1942-46), he received the Sc.D. in Structural Engineering from MIT in 1949. The same year he joined the Department of Civil Engineering of the University of California at Berkeley (UCB) as Assistant Professor. His chief lifelong research interest was structural dynamics. He spent the 1952-53 recesses with Turner's group at Boeing, supported by a Summer Research Program. He was exposed there to the baby FEM, and watched the paella being cooked. Why did a Civil Engineering faculty got involved in a hard-core Aerospace project? Two strong side motivations: family at Seattle, and proximity to his beloved Cascades mountains. At MIT he had learned matrix structural analysis from Bisplinghoff (a famous aeroelastician, who in turn had learned it from the book of Frazer, Duncan and Collar, the creators of the subject). He put that knowledge to good use in the matrix derivation of the plate and spar elements (all of which were built, by the way, by assumed stress pattems and *not* from assumed displacements). Back at UCB, the encouraging progress turned him into a "FEM preacher" to Civil Engineering colleagues around the world. One of which happened to be Olek Zienkiewicz, then a junior faculty at Northwestern. His reasoning: if the new method worked for the dynamics of complex aerospace structures, it should also perform well for Civil Engineering ones subject to dynamic loads such as earthquakes, hurricanes, or dam overspills. Two promotion obstacles remained: difficult computer access, and a method with no name.

Computer Access Improves, And Baby Gets A Name

In 1957 the first compiled computer language, Fortran I, was released. Although initially restricted to IBM hardware, it soon migrated to other platforms. Its effect on engineers and scientist with computer access was immense. For the first time those untrained in the mysteries of machine language could directly code applications, such as FEM, in a machine-independent way. Access eventually included graduate students. The seeds of CS departments began forming in Mathematics and Electrical Engineering departments. Availability also improved: by the late 1950s major universities begin purchasing computers, although resource allocation stayed limited. The UCB instance is typical: a

single mainframe (an IBM 704, less powerful than a current PC) served the entire campus.
The Civil Engineering Department at UCB expanded rapidly in the late 1950s benefiting, like most US schools, from the post-Sputnik funding frenzy. Over 100 faculty; four Divisions in separate buildings. Clough fought to introduce computer methods and FEM into the SESM (Structural Engineering and Structural Mechanics) Division, struggling against traditional academic distrust of innovative methodologies. Two important 1960 milestones helped his cause.
(1) The first application of FEM to an existing Civil structure, the cracked Norfork Dam, was done by Ed Wilson, then a doctoral student. The easy treatment of heterogenous media (structure and soil) was an eye opener to professional engineers, including those familiar with finite differences.
(2) The method name appeared in a 1960 ASCE Conference Proceeding volume. Clough's account: he concatenated "finite difference" + "structural element" and discarded the two midwords.
The name clicked and was soon well established. An informal FEM group began taking shape at the UCB SESM Division with the hiring of Ed Wilson and Bob Taylor as faculty in 1963. Other professors (notably Popov, Scordelis, and Pister) began incorporating FEM into courses and research projects.

The BS Connection

Olek Zienkiewicz ' first contact with Ray Clough dates back to 1958. At the time Zienkiewicz was a junior faculty at Northwestern University. He would move to the University of Wales at Swansea (UWS) in 1961 to become Chair of the Civil Engineering Department. His interest in computational methods in engineering dates to his Imperial College years, when he was a student of Sir Richard Southwell, a well known pre-computer guru of the Finite Difference Method (FDM). Through Clough's encouragement, he eventually (by 1964) recognized its enormous power. Goodbye FDM, hello FEM. With a convert's zeal he set about to build and lead his UWS research group to international preeminence. He co-wrote the first FEM book (Wiley, 1967) with Y.K. Cheung. He coedited with Dick Gallagher the first journal (Wiley, 1970) devoted entirely to numerical methods in engineering. Those dissemination vehicles greatly helped to carry FEM beyond structural mechanics. The personality contrast with other First Generation contributors is striking. For example, Turner and Clough viewed FEM as just a useful tool for engineers, and cared little about theoretical sugar.

Clough in fact gave up FEM research in 1972 once it got "too mathematical" for his tastes, and went back to his enduring love: earthquake structural dynamics. Turner went into management and became Chief Scientist at Boeing. But Zienkiewicz was genuinely interested in computational methods and on forming disciples to carry forth the message. His charismatic personality and laid-back leadership style certainly helped. In Zienkiewicz' 2009 obituary, Roger Owen recalls a comment by Tinsley Oden when they first met: ``Olek's intense interest and warmth was intriguing. We hit it off immediately."

What If …

Lets consider now one of Everett's parallel universes. And keep an eye on the fluttering butterfly. Suppose that Ray Clough is born in 1920 at Boston, not Seattle. He goes to MIT to get a PhD. Joins UCB as Civil Engineering faculty, but as a Massachusetts flatlander he does not care about mountaineering, preferring instead to sail. No summer visits to Boeing. No BB connection. No early FEM development at Berkeley. No bonding with Olek Zienkiewicz, who continues working in FDM all his life: a steady research area but not one conducive to explosive growth. Eugenio Oñate never hears about the famous Swansea group since there is no group. Upon graduation he joins an engineering design and construction company in Valencia, and does well. But no CIMNE. And this story would not be written.

CIMNE Comes Into Existence

In this universe the finicky butterfly took the right path. Personal connections clicked. The last one, between UWS and CIMNE, will likely be addressed in detail by other contributions to this dedicated volume.I just want to recall that my second scientific visit to Spain, and first to Barcelona, happened in 1984 to attend a conference co-organized by Eugenio Oñate, Roger Owen and Ernie Hinton. The close linkage with Swansea was obvious. Eugenio told me of his ambitious plans, which resulted in the formal creation of CIMNE three years later. Indeed the timing for that event was propitious. Spain was entering a period of economic expansion. Joining the European Union (EU) soon after facilitated mobility and brought human and financial resources. The rest, as they say, is history.

Concluding Remarks

As noted, CIMNE incorporated from start several of the features and traits of Zienkiewicz' group. These include: international outreach publicized by heavy emphasis on conferences and publications; interdisciplinary projects; incubated spinoffs. The main difference is one of scale. CIMNE presently employs over 100 researchers and staff, which makes it the largest Center of its type in the EU. Its remote educational outreach (the *aulas de CIMNE* network) fulfills an important educational mission. Interaction with professional and academic organizations worldwide keeps steadily rising. Its technology products are channelled through spinoff enterprises. Publication and conference activities continue unabated.

As the 25th anniversary rolls along, one may certainly state that CIMNE has *achieved a critical mass*, It should be ready to roll along to further activity levels if facilities expansion as well as synergistic connections with other institutions are achieved.

Happy silver anniversary! And to quote Bob Dylan: may you stay forever young.

***Comments on the by Ed Wilson on* December 22, 2012**

Hi Carlos,

I found your summary of Ray's early contributions to the field of computational mechanics very entertaining. However, you forgot the Portugal - Norwegian connection and many of your contributions.

Ray was on Sabbatical leave in Trondheim during the 1956-57 academic year. This is where he read Argyris' papers and decided to solve problems in continuum mechanics by the Finite Element Method. After his return to Berkeley in the Fall Semester of 1957 he indicated, <u>in writing</u>, he was inviting students to conduct research on the finite element analysis of membranes, plates and shells. For my MS Degree in 1958, I wrote a semi-automated two-dimensional stress program for the vacuum-tube IBM 701, which had a maximum of 4,096 locations of 16 bits memory, using a Symbolic Assembly Program, called SAP. The computer only had the ability to solve 40 simultaneous equations. During the same period Ari Adini used a matrix interpretive system to work the examples in Clough's 1960 paper given at the ASCE conference in Pittsburgh (the first "Finite Element" paper). I traveled with Ray to Pittsburgh (shared a room) and I presented a paper called "Matrix Analysis of Non-Linear Structures".

In September 1962, Ray, Jim Tocher and I received invitations to participate in a NATO workshop and conference in Lisbon, Portugal where we all presented papers. Jim, Mab and their baby Tommy were on their way to Trondheim to spend a year as a Post Doc. Ray and I presented a paper titled "Stress Analysis of a Gravity Dam by the Finite Element Method". This paper was selected to be published in the RILEM Bulletin No. 19, June of 1963. At that time, RILEM was an international publication with a very large circulation. This paper clearly illustrated that complex civil engineering problems could be solved by the Finite Element Method. I will mail you an original reprint of this paper if you do not have a copy.

After spending a year in Norway, Jim went to work at Boeing and a few years later, after your Post Doc at Cal, you joined him there. Therefore, the Butterfly effect has had a significant effect on your life. Without Ray, you might have been a cowboy in Argentina.

Happy Holidays,

Ed