BIOGRAPHICAL MEMOIRS

# Ted Belytschko

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Elected to the NAS, 2011

*A Biographical Memoir by Thomas J.R. Hughes*

**Ted Belytschko was** one of the most cited and influential researchers in the history of computational mechanics. His earliest work focused on structural dynamics and explicit transient analysis algorithms for short intensity dynamic events, such as response of structures to explosions and crash dynamics. He was a key figure in developing efficient shell finite elements and algorithms for impact early in his career, and this work was implemented in the most widely utilized commercial crash dynamics codes, in particular, LS DYNA. They are now standard design tools for the entire automotive industry and have led to generations of safer vehicles.

Ted also was the prime mover in the "meshless methods" revolution, authoring a seminal paper on the so-called "element-free Galerkin method," which described a procedure that freed the discretization from element mesh topology. That freedom led to many successful applications to problems that were very difficult to solve with traditional methods, such as very large deformation problems in which mesh distortion would cause finite element calculations to fail. His initial paper is one of the landmark contributions to computational mechanics. Another area that Ted and his students and postdocs pioneered is the "extended finite element method," better known as XFEM, which is the extension of finite element technology to discontinuous kinematics. It has had enormous impact, especially in fracture and crack propagation. Ted also made significant contributions to molecular dynamics and quantum mechanical simulations, and the synthesis of particle and continuum methods that have been largely directed toward problems of failure mechanisms in solids and structures, a consistent theme in much of Ted's work.

Ted Belytschko was born in the town of Proskurov in Western Ukraine on January 13, 1943, during the height of World War II. He was named Bohdan Belytschko by his parents, Stephan and Maria Belytschko, and was their only child. Eventually, the family emigrated to the United States, arriving in Chicago in December 1951. No one in the family spoke English, but young "Ted," as he was now known, picked it up quickly. His father encouraged academics, and Ted soon received a scholarship to the Francis Parker Preparatory School in Chicago. From there he entered Lane Technical High School (what would today be a magnet school), also in Chicago, and graduated as valedictorian. He

entered the Illinois Institute of Technology on a full scholarship in 1961. He received his bachelor of science degree in 1965, again as valedictorian, and began graduate work there under the direction of Philip Hodge. Ted met Gail Eisenhart at Illinois Institute of Technology in 1964 and they married in 1967; the couple would have three children, Peter, Nicole, and Justine. Ted earned a Ph.D. in 1968 and accepted a position at the University of Illinois at Chicago Circle (now the University of Illinois at Chicago). He joined the faculty at Northwestern University in 1977 and remained there for the rest of his career.

Ted was the Robert R. McCormick Institute Professor and Walter P. Murphy Professor of Mechanical Engineering and Civil and Environmental Engineering at Northwestern. He chaired the Department of Mechanical Engineering from 1997–2002. Students enjoyed his sense of humor and emphasis on precise but simple explanations and methods. Ted provided his Ph.D. students with numerous research ideas to pursue, but he also gave them freedom in choosing their research topics, along with the guidance to avoid pitfalls and low-impact pursuits. He devised many promising areas of research and fully understood their practical potential, often long before his students even believed they would work at all. Here is an example in some recollections of John Dolbow, one of Ted's former Ph.D. students:

> "I was at Northwestern during what I believe to be a fairly special period for Ted. His group had very much ramped up on meshfree methods, and towards the end transitioned to the XFEM. He had a healthy research group and there was a lot of spirited debate around theory and methods. There were some very smart people around. Tom Black, Sukumar, Petr Krysl, and Nicolas Moës were all there at that time, just to name a few.
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> "Probably the most important thing I can tell you concerns what gave rise to the XFEM. Tom Black approached me just before I left one summer to spend a practicum at Los Alamos. As would often happen, we met late at night for coffee in the small cafe on the first floor of the Tech building at Northwestern. At that time Tom told me that Ted had this "crazy idea" to put cracks right in the middle of finite elements, with a sprinkling of element-free Galerkin nodes around the crack tip to capture the singularity. I agreed that this was a crazy idea that definitely would not work. I wasn't alone in this assessment, everyone else in the group thought it was crazy too. Well as it happens Ted was fairly persistent about this one, and when I came back at the end of the summer the Belytschko and Black paper on minimal remeshing was basically done. That work paved the way for essentially my entire Ph.D. thesis. It introduced a way of viewing the finite element method that was there for all of us to see but that only Ted had really had the vision to imagine before anyone else.
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> "The work I did on the XFEM during my last year at Northwestern formed the basis of the paper I submitted for the Melosh Competition that year. I did not have any awareness of this competition before Ted told me about it and told me to apply for it. He also told me that he expected me to win the competition and that the work was good enough that it should win. No pressure, right?"

Here are more recollections of John Dolbow about Ted as a mentor:

> "My other memories aren't so much about science as they are Ted's role as an advisor and confidant. Group meetings were held on Fridays jointly with Wing Kam Liu's group and Brian Moran's as well. Typically, a single graduate student from one of the research groups would present a topic to everyone else. They could be brutal. You had to be prepared. Ted didn't have much tolerance for a lack of precision or clarity in the presentations. It prepared his students for a lot. I've shared this with many people, but there was a week towards the end of my stay there when I had two faculty interviews and a presentation in the group meeting on Friday. The only one I was nervous about was the group meeting.
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> "But Ted was funny in those meetings too. He also had a line I'll never forget, which came about when he decided his group wasn't quite working hard enough. He said 'More of you need to start coming in on Saturdays. This is not a vacation spa.' And then he smiled the way he always did to let you know that he thought this was a pretty clever thing to say, but also that he was the boss.
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> "Well, I was always there on Saturdays, and the funny part is that those are some of my fondest memories of Ted. He would often swing by right after a morning swim, in a full tracksuit. He was always keen to hear how the latest idea or paper was coming along, or just to discuss computational mechanics and finite elements in general. Ted lived, breathed, and slept computational mechanics."

Jacob Fish, another of Ted's PhD students recalls Ted's creativity:

> "One of the first things at Northwestern University we quickly learned is Ted's unique ability to originate new ideas at a torrential pace. With a birth of each new idea, Ted would call one of his Ph.D. students to discuss the implementation of his latest idea. Each of us would have an increasingly long list of ideas that have to be explored, pretty much by yesterday.

"Ted taught us that both quality and quantity of research matters. Every three to five years, he would say, make sure that you produce at least one outstanding contribution, and then sprinkle in with follow up contributions. He would remain true to his own teachings by constantly producing seminal contributions, such as the corotational framework, one-point integration and stabilization, continuum theory of strain-softening, probabilistic finite elements, the element-free Galerkin method, the celebrated XFEM, and atomistic-continuum coupling.

"To his graduate students, Ted liked to quote Arno Penzien, the Noble Prize laureate, who said: 'There are two types of scientists: two percent discover new things and blaze new frontiers, the other ninety-eight percent fix up their mistakes; the accolades go to the former.' Ted certainly belonged to the former, and he encouraged his graduate students to pursue the same."

J. S. Chen, another of Ted's Ph.D. students, also recalls Ted's research philosophy:

"Ted always said that simple and fundamentally sound methods win the game. Many of his ingenious inventions of computational methods embodied this spirit, such as hourglass control of one-point quadrature rule elements, the Belytschko-Tsay shell element, explicit finite element methods, the pinball algorithm, meshless methods, and the extended finite element method, among others. I later realized that the concept of keeping things simple applies not only to research but also to life. When I was deciding on a career change, with many factors to consider, Ted told me to think about what would give me a better opportunity to do great work. This was a simple and strong message and helped tremendously for my decision to move on."

I first met Ted through one of his papers. It was 1975, and I had recently completed my Ph.D. at the University of California, Berkeley. The paper was an investigation of the stability of finite element methods and time stepping algorithms for nonlinear structural dynamics. I was thinking about this problem, too. I found Ted's paper very interesting and mentioned it to Ed Wilson. Ed told me that he had recently heard Ted deliver a paper at a conference and was very impressed by him. I suggested that we invite Ted to visit Berkeley and present a seminar. The day he visited I agreed to meet him at the Civil Engineering Department Office. When I arrived, I saw an individual standing by the door of the office wearing an overcoat and a hat. I knew it was our visitor from Chicago because no one from Berkeley would be wearing an overcoat and a hat on a warm and sunny California day. Ted presented a seminar that morning, and after it we went to lunch at the Faculty Club with Ed and Bob Taylor, whom I was working with at the time. Ted enjoyed the opportunity to meet Ed and Bob, who already were finite element luminaries. We had interesting discussions about research, finite elements, and nonlinear mechanics that lasted throughout the day. Ted's congenial personality and hearty sense of humor were immediately evident. I really liked him. We hit it off, became friends, and always remained friends.

Ted and I attended many of the same conferences, served on many of the same committees, and were funded by some of the same funding agencies. We spent a lot of time together at various meetings and we always had interesting things to talk about, usually over a good dinner.

One of the things that we will forever be jointly identified with is the Nonlinear Finite Element Short Course that we taught together for thirty years in Europe and the U.S. It was aimed at industrial users of nonlinear finite element software and Ph.D. students and postdocs doing research in computational mechanics. We had many nice social events in concurrence with the courses and always celebrated at the end of a course with a special dinner at the best restaurant we could find, at which we ordered a special bottle of wine to share. It was great fun.

Ted and I worked very hard on the technical content of our short-course lectures and tried to make the courses the best they could be. After a while, Ted started to add some jokes to his lectures. In one of the course evaluations, an attendee proclaimed that the thing he liked best about the course was "Professor Belytschko's jokes."

Ted was elected to the National Academy of Engineering in 1992, the American Academy of Arts and Sciences in 2002, and the National Academy of Sciences in 2011. He was elected a fellow of the American Society of Mechanical Engineers (ASME) in 1978, the American Academy of Mechanics in 1979, and the American Association for the Advancement of Science in 1989. Ted also received honorary doctorates from the University of Liège, Belgium, in 1997, the École Normale Supérieure, Paris, France, in 2004, and L'Institut National des Sciences Appliquées de Lyon, France in 2006.

He received the Pi Tau Sigma Gold Medal from ASME in 1975, the Walter Huber Research Prize from the American Society of Civil Engineers (ASCE) in 1977, the Thomas Jaeger Prize from the International Association for Structural Mechanics in Reactor Technology in 1983, the Computational Mechanics Award of the Japanese Society of Mechanical Engineers in 1994, the Melvin Baron Medal from the Shock and Vibration Information Analysis Center in 1999, the Theodore von Karman Medal from ASCE in 1999, the John von Neumann Medal of the U.S. Association for Computational

Mechanics (USACM) in 2001, the Timoshenko Medal from ASME in 2001, the Gauss-Newton Medal of the International Association for Computational Mechanics (IACM) in 2002, and the William Prager Medal from the Society of Engineering Science (SES) in 2011. In 2013, Ted was elected an honorary member of ASME for a lifetime of service to the profession.

In 2007, the Applied Mechanics Division (AMD) of ASME renamed its AMD Award the Ted Belytschko Applied Mechanics Award. Ted was a Founding Director of USACM, and in 2012, its Computational Structural Mechanics Medal was renamed the Ted Belytschko Medal. He served terms as vice president for the Americas of IACM, president of the American Academy of Mechanics, and chairman of the U.S. National Committee on Theoretical and Applied Mechanics.

In 2013, the McCormick School of Engineering at Northwestern initiated the Ted Belytschko Lecture series in honor of Ted, which recognizes Ted's impact on the Mechanical Engineering and Civil and Environmental Engineering departments. The series brings a prominent speaker to the university each year. In 2017, the Mechanical Engineering Department at Northwestern established the Ted Belytschko Outstanding Research Award for Ph.D. students.

Ted also served as editor-in-chief of the *International Journal for Numerical Methods in Engineering* and on numerous other archival journal boards. He served on the scientific and organizing committees of many national and international conferences and was a consultant to more than twenty companies and national laboratories.

The bibliography that follows cites some of Ted's most important archival journal publications on meshless methods and the extended finite element method, as well as his book on nonlinear finite element analysis.

Ted Belytschko's research gained the admiration of the academic community and enjoyed widespread industrial and commercial utilization. His publications achieved enormous citation impact. He richly deserved and received many honors, awards, and accolades throughout his career. He gave beautifully clear lectures, a quality that was also present in his written works. He encouraged and supported young scholars and always had time for discussions with them about engineering science and the professional challenges they faced.

Early in 2010, Ted suffered a massive stroke secondary to intermittent atrial fibrillation. He worked very hard at rehab and with the support of colleagues, postdocs, and students continued his academic activities until medical complications related to the stroke overwhelmed him. He died on September 15, 2014, in Evanston, Illinois.

The last four and a half years of Ted's life were an ordeal for Ted, his loving wife Gail, his children, their families, and caregivers. Ted was a very special person and one of the giants of computational mechanics. As those last years fade in my memory, I remember him as he was in his prime: energetic, hard-working, productive, passionate, brilliant, creative, witty, and a kind and generous friend.

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