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The impact of Yibin Fu's work: In recognition of his 60th birthday

This special issue of the International Journal of Solids and Structures is dedicated to Professor Yibin Fu, to celebrate his 60th birthday and to recognize his transformative contributions to the field of nonlinear continuum mechanics. In the following, we recap his career to date, highlight some of his main contributions and, for reference, include a list of his published works so far (Yan and Fu, 1988; Fu and Scott, 1988, 1989a,b,c,d; Hall and Fu, 1989; Fu and Scott, 1990, 1991a,b; Fu and Hall, 1992; Fu et al., 1993; Fu and Hall, 1993; Fu and Scott, 1993; Fu, 1993; Fu and Li, 1993; Fu, 1994; Fu and Hall, 1994; Fu and Rogerson, 1994; Rogerson and Fu, 1995; Fu, 1995; Ogden and Fu, 1996; Fu and Devenish, 1996; Fu and Zheng, 1997; Devenish and Fu, 1997a,b; Fu, 1998b,a; Fu and Ogden, 1999; Cai and Fu, 1999; Fu, 1999; Cai and Fu, 2000; Fu et al., 2000; Erbay et al., 2000; Zhang and Fu, 2000, 2001; Fu and Hill, 2001; Fu, 2001; Fu and Sanjarani Pour, 2002; Fu and Mielke, 2002; Fu and Lin, 2002; Fu, 2003; Mielke and Fu, 2004; Fu and Freidin, 2004; Fu, 2005a,b; Fu and Brookes, 2006b; Destrade and Fu, 2006; Fu and Zhang, 2006; Fu and Brookes, 2006a; Freidin et al., 2006; Fu, 2006; Song and Fu, 2007; Fu, 2007; Destrade and Fu, 2008; Fu et al., 2008; Edmondson and Fu, 2009; Li et al., 2009; Fu and Ilichev, 2010; Pearce and Fu, 2010; Fu and Xie, 2010; Fu and Kaplunov, 2011; Fu et al., 2012; Fu and Xie, 2012; Ilichev and Fu, 2012; Fu et al., 2013; Fu and Xie, 2014; Ilichev and Fu, 2014; Fu and Ilichev, 2015; Fu and Ciarletta, 2015; Ciarletta and Fu, 2015; Fu and Cai, 2015; Xie et al., 2016; Destrade et al., 2016; Geng et al., 2016; Fu et al., 2016; Geng et al., 2017; Wang et al., 2017; Wang and Fu, 2018; Fu et al., 2018a,b; Zhou et al., 2018; Wang et al., 2019; Cai and Fu, 2019; Ye et al., 2020; Fu et al., 2020c; Dimmock et al., 2020; Wang and Fu, 2020; Fu et al., 2020a,b; Ilichev et al., 2020; Yu et al., 2020; Wang and Fu, 2021; Emery and Fu, 2021b,a,c; Yu et al., 2021; Zhou et al., 2022; Yu and Fu, 2022; Wang et al., 2022; Guo et al., 2022; Wang et al., 2023; Yu and Fu, 2023; Fu and Yu, 2023; Fu, 2024).

Yibin was born on 31 January 1964 in Hunan Province, China. In 1978, at the young age of 14, he was admitted to Central South University, where he obtained a BSc in Mathematics and Mechanics in 1982. After a one-year training at Tianjin University, he moved to the UK to pursue a PhD, following an intensely competitive process. He completed his doctoral studies at the School of Mathematics and Physics, University of East Anglia, in 1988. At the time, the school had one of the strongest groups in applied mathematics in the UK, and was led by Professor Peter Chadwick FRS. Yibin's PhD thesis was titled "Weak shock waves in nonlinear elastic solids" and was supervised by Dr Nigel Scott (who was a Ph.D. student of Professor Mike Hayes, himself a former Ph.D. student of Ronald Rivlin).

In the 1970s and 1980s, interest in nonlinear waves mostly focused on acceleration waves governed by a simple evolution law. In contrast, the evolution of shock waves is coupled with the evolution of higher-order discontinuities, and because of the resulting complexity, was rarely studied. Focusing on shock waves of small amplitude, Yibin derived explicit evolution laws for shock waves of various geometries (Fu and Scott, 1988, 1989a,b,c,d; Hall and Fu, 1989; Fu and Scott, 1990, 1991a,b). One of the methods he used was the shock-fitting method based on the equal-area rule, borrowed from gas dynamics. Transferring ideas from other disciplines is a recurring feature of Yibin's work and a hallmark of his research.

Yibin spent three years as a post-doctoral research fellow working on the instability of hypersonic boundary layers. In 1991 he returned to solid mechanics after securing a Lecturer position at Manchester University, and very quickly established himself as an independent researcher. Six years later he moved to Keele University as a Senior Lecturer, was promoted to Reader in 1999 and became Professor of Applied Mathematics in 2001. In 2012, he became Adjunct Professor at Tianjin University, where he helped establish a research group in nonlinear elasticity and mechanics of soft materials.

One of the first topics that attracted his attention was the propagation of nonlinear surface waves. It was already well-known in the nonlinear wave community that the existence of a steady nonlinear wave requires two ingredients: nonlinearity and dispersion. Although there is no natural length scale associated with a homogeneous hyperelastic half-space and hence no dispersion, some researchers still hoped that a steady nonlinear surface wave might exist due to the nonlocal nature of the nonlinearity, and such solutions were indeed reported in the literature. However, Yibin showed that the calculations leading to the finding of steady nonlinear waves were flawed and concluded that such waves should not exist. Moreover, a number of approaches were used for deriving the evolution equations, some extremely involved, and the resulting equations were all seemingly different. By proposing a virtual work method, Yibin was able to drastically simplify the

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derivations of evolution equations and, in doing so, was able to show that all the existing methods except one would yield the same evolution equations (the odd one was in fact not asymptotically self-consistent (Fu, 2006)).

It was around that time that Yibin made his first attempt at modelling crease formation in a compressed elastic half-space, long before it became an active topic of research in the literature. Yibin considered the buckling of a half-space, whose free surface has sinusoidal corrugations, and showed that the corrugations would evolve into static shocks as the lateral compression increased (Fu, 1999). He then conjectured that smooth post-buckling solutions of a compressed elastic half-space cannot exist and that the possible solutions are static shock waves. In hindsight, this conjecture is consistent with the observation of a crease as we know it today.

The virtual work method was next extended and used in one of the earliest post-buckling analyses within the framework of nonlinear elasticity in collaboration with Professor Zongxi Cai of Tianjin University. Driven entirely by curiosity, they carried out a weakly nonlinear post-buckling analysis of a coated hyperelastic half-space under lateral compression (Cai and Fu, 1999). They showed that there exists a threshold stiffness ratio such that the bifurcation/buckling will be supercritical if the coating is sufficiently stiff compared with the substrate, and subcritical otherwise. A coated half-space is nowadays more commonly referred to as a film/substrate bilayer and the topic has since become a very active area of research, inspired by the experimental study by Bowden et al. (1998, Nature), who predicted that micro- and submicro-metre wrinkles could serve as functional patterns. Cai and Fu's results are consistent with the later findings that patterns in stiff film/soft substrate bilayers tend to evolve stably all the way into patterns with higher periods (because the post-buckling solutions associated with a supercritical bifurcation are generally stable).

Yibin's next major research topic was the characterization and stability analysis of two-phase piecewise-homogeneous deformations, carried out in collaboration with Professor Sasha Freidin based in St Petersburgh. By modelling the interface as a sharp surface with zero thickness and the material as being hyperelastic, they systematically characterized the strain–energy functions that admit such two-phase solutions and the domains of deformation that each phase may take for a stable solution (Fu and Freidin, 2004). Inspired by this analysis, Yibin later proposed a continuum mechanical theory for describing kink bands in fibre-reinforced composites (Fu and Zhang, 2006).

He also pioneered the use of the WKB method for buckling analysis in the framework of nonlinear elasticity. His first paper on this method provided interesting insights into the buckling of a spherical shell of arbitrary thickness (Fu, 1998b). His skills in asymptotic analysis were also demonstrated in his later study of cavitation in an elastic plane membrane, where he was able to deduce the near-critical behaviour of the cavitation solution analytically (Geng et al., 2017).

Although Yibin's research had focused on nonlinear waves and post-buckling analysis up to this point, he always kept an interest in Stroh formalism and linear surface waves since his PhD days, influenced by Professor Peter Chadwick's presence. Peter was a leading expert on Stroh formalism and had given many seminars and talks that Yibin attended. However, it was not until 10 years later that Yibin made his first contribution to the study of surface waves and Stroh formalism. By collaborating with Professor Alex Mielke, based in Stuttgart, he showed that the surface impedance tensor satisfies a quadratic matrix equation (a Riccati equation) from which many useful properties were deduced (Fu and Mielke, 2002; Mielke and Fu, 2004). Although it was later realized that the same Riccati equation had in fact previously been derived by S.V. Biryukov (1985, Sov. Phys. Acoust.), some of the properties deduced remained novel and insightful. Around the same time, Yibin showed that the reason that the Stroh formulism enjoys so many interesting properties is that it is in fact a Hamiltonian formulation (Fu, 2007). It then follows that any problem that admits a variational principle will admit a Stroh formulation. This observation significantly widens the applicability of the Stroh theory.

Yibin's attention in recent years has been focused on the age-old problem of localized bulging of an inflated hyperelastic tube. Prior to Yibin's study, there already existed many experimental results but analytical understanding/characterization of this phenomenon was very limited. When (almost) any commonly-used strain energy is used to plot the pressure against volume in uniform inflation, it is found that it has an up–down–up behaviour. This fact led Yin (1977, J. Elast.) and Chater & Hutchinson (1984, ASME J. Appl. Mech.) to show that the propagation pressure can be derived using the equal area rule. However, their analyses are only valid in the case of fixed axial force (e.g., when one end of the tube is closed and free to move in the axial direction), and it is not clear how the propagation pressure could be determined if the tube is pre-stretched prior to inflation and both ends are fixed during inflation. More importantly, these studies do not seem to have any connections with the linear bifurcation study carried out by Haughton and Ogden (1979, J. Mech. Phys. Solids) for a rubber tube that is axially stretched and inflated. Yibin proposed that localized bulging can be viewed as a bifurcation with zero wavenumber, and he demonstrated explicitly how a localized solution bifurcates from the uniform solution, grows to a maximum amplitude in radius, and then propagates in the axial direction. Once this had been established, he, with various collaborators, was able to apply the same technique to provide insight into localized necking induced by surface-tension (Fu et al., 2020a; Emery and Fu, 2021b,a,c) or by an electric field (Fu et al., 2018a,b). These latter studies highlight the fact that although localized necking was not supported by traditional materials in uniaxial tension in the elastic regime, it may be a common occurrence in modern smart materials under multi-fields. In uniaxial tension, a necessary condition for the occurrence of necking or bulging is that one force variable against the corresponding conjugate deformation variable has a maximum (or limit point) when the other force variables are fixed. However, Yibin has recently demonstrated that in all-round tension (or equivalently equibiaxial tension), the bifurcation point for axisymmetric necking may be reached before the limit point, and has hence developed a complete theory to describe this new scenario (Wang et al., 2022; Fu and Yu, 2023). In particular, the amplitude equation describing the near-critical behaviour seems to be quite novel: it is a fourth-order quadratically nonlinear ordinary differential equation with variable coefficients and it admits axially symmetric solitary wave type solutions. These studies are summarized in his CISM lecture notes published in 2024 (Fu, 2024).

Related to the localized bulging of an inflated hyperelastic tube is the propagation of solitary waves in such a tube when the internal pressure is sufficiently small: a localized bulge is simply a solitary wave with zero propagation speed (induced by the internal pressure). There exist numerous studies of this problem based on ad hoc models, most of which ignore the axial displacement to simplify the analysis. In collaboration with Professor Andrej Ilichev from the Steklov Mathematical Institute in Moscow, Yibin provided a complete and exact study of solitary waves within the framework of nonlinear elasticity (Fu and Ilichev, 2010; Ilichev and Fu, 2012, 2014; Ilichev et al., 2020). In particular, he provided the first proper derivation of the pulse wave speed that takes full account of material nonlinearity and prestress in arteries (Fu and Ilichev, 2015).

Yibin has maintained his strong interest in the wrinkling of a film/substrate bilayer and has continuously published results on this topic since his early paper in 1999. His most recent contribution, in collaboration with Yang Liu at Tianjin University, is the derivation of an asymptotically self-consistent theory that refines the Euler–Bernoulli beam model and the Winkler foundation assumption (Wang et al., 2023). This combination was commonly used in the engineering community to approximate the deformation of a stiff beam bonded to a soft foundation and variants of this combination have been commonly used in the buckling analysis of film/substrate bilayers. Yibin and Yang derived the next-order correction, thus giving a higher-order theory for the deformation of a stiff beam on a soft foundation. In this theory, the response of the foundation is described exactly by taking the surface impedance tensor and shear force (although of higher order) into account at the interface. In the absence of the foundation, the refined theory recovers the static part of the Timoshenko beam theory.

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