New research reports on buckling: When structures suddenly collapse

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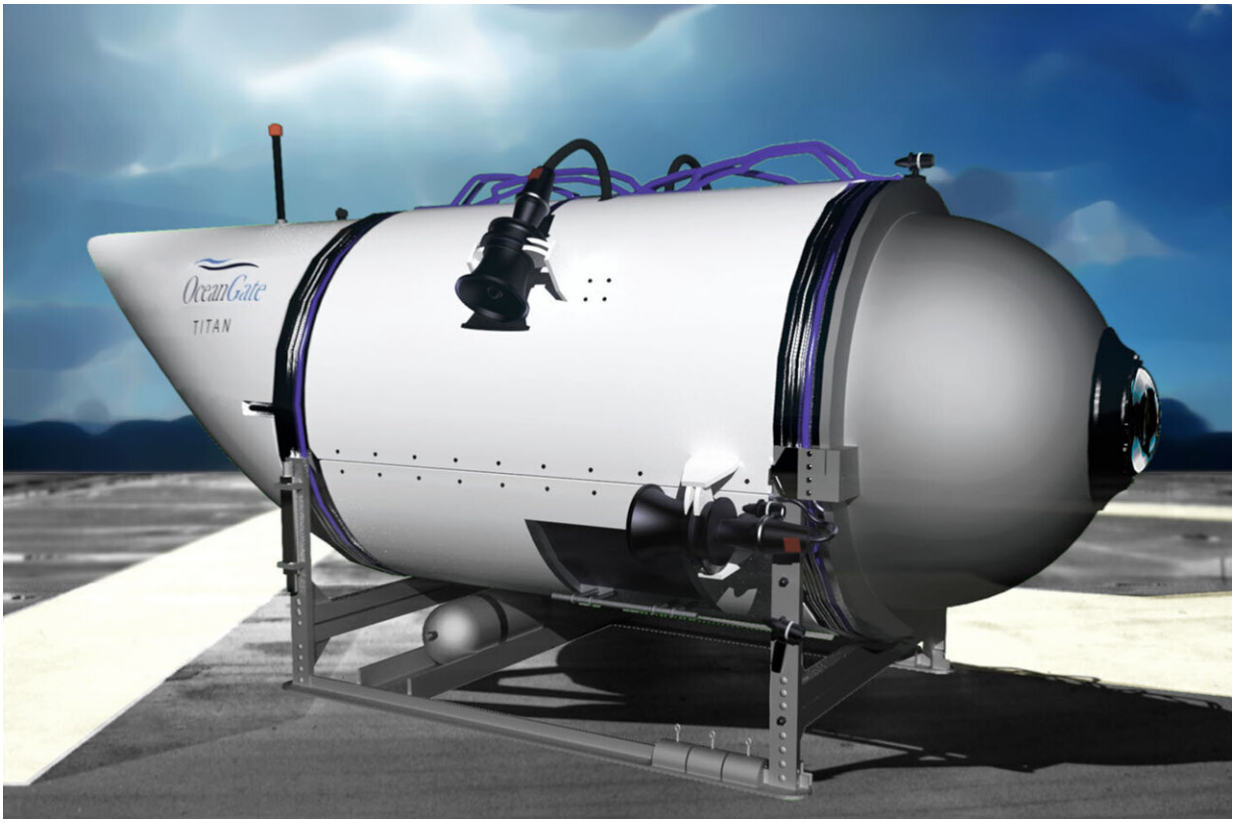

Model of the Titan submersible on deck. It is one example of a thin-walled structure. Credit: Wikimedia Commons, CC BY-SA 4.0

Last summer, when the Titan submersible suffered a catastrophic implosion on its way to take passengers to see the Titanic shipwreck, it

was a dramatic example of the failure of a thin-walled structure. Those structures, which may be in the shapes of spherical or cylindrical shells, can efficiently carry relatively large loads, but their slenderness makes them susceptible to buckling-induced collapse.

The submersible is not the only thin-walled structure you may interact with. Whenever you step into a car or hop aboard a plane, you are entering one. They all looked perfectly formed on the drawing board, but when manufactured, they don't all come out quite so perfectly and can contain geometric imperfections. The structures will buckle at much smaller forces because of these imperfections than they would if they were perfectly shaped.

Until now it has been impossible to accurately predict the detrimental effects of geometric imperfections, but Roberto Ballarini, Thomas and Laura Hsu Professor and department chair of Civil and Environmental Engineering, is changing that. He reports in the *Proceedings of the National Academy of Sciences (PNAS)* a theoretical equation, based on the results of computer simulations, that predicts the average buckling strength of a shell based on the parameters that describe the imperfections.

Of course, advanced math is involved.

"We derived equations that allow us to predict the resistance to buckling of structures in terms of the parameters that are involved including the shapes and distribution of their imperfections," reports Ballarini. "Given the parameters that describe the imperfections, the equations we constructed using the results of the simulations 'spit out' the average buckling resistance of the structures."

Ballarini coauthored the *PNAS* paper with doctoral student Zheren Baizhikova and Jia-Liang Le, a professor at the University of Minnesota.

"Localized deformation and randomly shaped imperfections are salient features of buckling type instabilities in thin-walled load-bearing structures. However, it is generally agreed that their complex interactions in response to mechanical loading are not yet sufficiently understood, as evidenced by buckling-induced catastrophic failures which continue today," the authors wrote.

Ballarini added, "One must not forget that a structure's resistance to buckling failure is also affected by the strength and stiffness of the material from which it is made."

Consider for example the tragic failure of the Titan submersible.

"Its integrity may have been compromised by the damage to the material used for its hull that accumulated during the many trips it took prior to collapse. The material used for the Titan's hull was a carbon fiber composite. It is well known that under compression, loading the fibers in such composites are susceptible to micro-buckling and that they may delaminate from the matrix that surrounds them," Ballarini said

"If the Titan's hull experienced such damage under the extreme compressive pressures it experienced during its dives, then its stiffness and strength would have significantly decreased, and together with the inevitable geometric imperfections introduced during its manufacturing, may have contributed to its buckling-induced implosion."

For a given shell, buckling initiates where the geometric imperfection is most severe, and since the spatial distribution of geometric imperfections is random, so is the location of the initial buckling zone.

"This randomness has profound implications for the statistics of the critical buckling pressure of the shell," said Ballarini, whose computer simulations and theoretical analysis allowed the research team to craft a

probabilistic model for the statistical distribution of buckling resistance that offers promise for creating lightweight and sustainable structures while ensuring their structural reliability without unnecessary over-design.

More information: Zheren Baizhikova et al, Uncovering the dual role of dimensionless radius in buckling of spherical shells with random geometric imperfections, *Proceedings of the National Academy of Sciences* (2024). DOI: 10.1073/pnas.2322415121 , www.pnas.org/doi/10.1073/pnas.2322415121

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