

Packaging as an Imperfection Signature: What Deployable Shells Lack That Welded Ones Have

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Abstract

Thin shells buckle well below classical theory, and the gap is governed by initial geometric imperfections. The empirical answer — a knockdown factor read from NASA SP-8007 — is a lower-bound envelope fitted to cylinder tests, and the sector has known its limits for a long time. The modern answer is already written down. SP-8007 was revised in 2020 to add an analysis-based design approach built on measured imperfections, and to define an *imperfection signature*: a geometric imperfection shape characteristic of a specific structural concept and manufacturing process. ECSS has recommended realistic, worst-case and stimulating imperfection analyses since 2010. The theoretical basis is older still, in Koiter's result that an imperfection's component in the critical mode governs first-order sensitivity.

So the method is not missing. What is missing for deployable structures is the input.

For welded metallic launch-vehicle cylinders the signature is characterised: measured, Fourier-decomposed, published, worth a reported 31 percent reduction in buckling load, and validated against full-scale tests. For a shell that is folded, stowed and deployed, the equivalent does not exist. The public record contains a single-specimen buckling test from 2000, a qualitative programme report from 2004, boom-specific analyses from NASA Langley and DLR, and a 2014 review that names the quantification gap explicitly. There is no data set, no published signature, and no design guideline. Neither SP-8007 Rev 2 nor the ECSS buckling handbook treats folding or stowage as an imperfection source at all.

This note argues that the gap is not an oversight but a structural consequence of how signatures are defined. A manufacturing signature is fixed at build: measure it once and it is a property of the design. A packaging signature is a function of the article's history — how many times it has been folded, how long it was stowed, and at what temperature. The existing apparatus assumes a static imperfection. Packaging breaks that assumption, and that is the part that has to be built rather than borrowed.

1. What is already settled, and by whom

Nothing in this note is a claim that imperfection sensitivity is poorly understood. It is understood very well, and the credit is long-established.

Koiter (1945) showed that the component of an initial imperfection lying in the critical buckling mode governs first-order imperfection sensitivity. Every later method that projects a measured field onto mode shapes is an application of that result.

Hutchinson has stated the limitation of the empirical factors about as plainly as it can be put: they are lower bounds to the existing experimental data, they fall further as more data accumulates, and there is nothing in the theory that attaches significance to any particular knockdown factor.

NASA SP-8007 was issued in 1965, revised in 1968, and — the point this note's earlier draft missed — **revised again in November 2020**. Revision 2 adds an analysis-based design approach built on measured imperfections, and defines the term this note is organised around: an *imperfection signature* is "a geometric imperfection shape that is characteristic of a specific structural concept and a manufacturing process." It shows a Fourier decomposition of a measured weld-land imperfection. It also says directly that the lower-bound factors come from cylinders manufactured and tested by outdated processes, and so may not represent other populations.

ECSS-E-HB-32-24A (2010) covers numerical analysis with realistic geometrical imperfections, worst geometrical imperfection, stimulating imperfections, manufacturing signatures, measured imperfections and the Imperfection Data Bank. It is a handbook — advisory rather than normative — but the method is there.

The European DESICOS project and the Single Perturbation Load Approach were developed precisely because an empirical lower bound says little about a specific structure.

A reader who concluded from an earlier framing of this subject that the author believed the deterministic-imperfection argument to be novel should disregard that framing. It is not novel. It is codified on both sides of the Atlantic, and the useful question is what it is being applied to.

2. What a characterised signature looks like

Welded metallic launch-vehicle cylinders are the worked example, and they are worth setting out because they establish what "characterised" means.

The weld land in an orthogrid or isogrid barrel is a located, systematic, design-determined imperfection. It is not random scatter: it lies where the welds lie, and the welds are on a drawing. It has been measured, decomposed into its Fourier components, and published. One NASA study reports that weld lands produced a 31 percent reduction in buckling load. The effect has been checked against full-scale test: a seamless 8-foot orthogrid barrel tested at Marshall in April 2017 buckled at 743,000 lb against a 697,000 lb pre-test prediction, roughly 28 percent above a corresponding welded cylinder. Knockdown factors derived from this work are in use on the Space Launch System.

That is the full chain: the imperfection is located, measured, represented, predicted, tested, and turned into a design factor that flies.

Note what it also establishes, because it undercuts an easy contrast. Manufacturing imperfections are *not* simply random. The whole point of the imperfection-signature concept is that a manufacturing process leaves a characteristic, located, repeatable shape. A folded shell is not distinguished from a welded one by being located and systematic. Both are.

3. What is known about packaging-induced imperfections

Less than the welded case, but considerably more than nothing. The relevant public work, as far as the author has found it:

Barker and Guest (2000) folded annealed aluminium tubes into a triangulated pattern, inflated them, and buckle-tested them against never-folded twins, stating the aim as determining whether the imperfections left by folding and inflation were critical. The folded tube failed at approximately 78 percent of the virgin load, and buckling initiated around the valley folds of the original fold pattern. This is a single specimen pair, and the authors themselves caution against over-reading it. It is nonetheless a direct measurement of a crease acting as a buckling trigger.

The ISAT programme (2004), reporting on rigidizable tubes tested at NASA Langley, found that after a small number of mechanical packaging and deployment cycles there were only minor changes in tube moduli but severe effects on compressive strength, and that further packaging cycles had rapidly decreasing effects. No percentages are given in the public report.

Greschik and Mikulas (1996) treated stowage creases as imperfections in aluminium-rigidized inflated cylinders.

Schenk, Viquerat, Seffen and Guest (2014), reviewing inflatable booms, state that material plastically deformed along fold lines leaves residual stresses and geometric imperfections; that residual creases can reduce the effective membrane modulus by up to two orders of magnitude at low stress; and, citing Senda, that a folded strain-rigidized boom's stiffness was reduced to about one third of an unfolded boom's, with no analytical or numerical studies found to characterise the effect. That last clause is a peer-reviewed statement of the gap, published twelve years ago.

NASA Langley (Fernandez, 2017) sets solar-sail boom requirements including a buckling load with a factor of two, and stowage limits of no more than 30 percent cross-section flattening and 10 cm axial curvature, reporting a measured 30 percent width loss that halves the critical in-plane buckling load — and proposing that such work could provide a future knockdown factor for imperfect non-straight beam-columns. A NASA author has therefore already proposed a knockdown approach for stowage-deformed booms.

Salazar and Fernandez (2021) report that prolonged stowage flattening can decrease boom buckling load by 50 percent. This figure appears to be derived from section geometry on a creep-prone laminate rather than from a back-to-back buckling test, and should be read accordingly.

NASA (2023), on self-erecting lunar towers, uses stowage-induced creep curvature as the initial imperfection in a beam-column buckling analysis. **DLR (2021)** predicts roughly 22 percent relaxation modulus reduction over 20 years and 11.5 percent boom height reduction for a deployable sail boom, with a subsequent buckling analysis.

The stowage-viscoelasticity literature is substantial and must not be presented as absent: Kwok and Pellegrino on viscoelastic tape springs, Brinkmeyer and co-workers on long-term stowage, DLR's creep programmes, work on shape recovery after extended coiling, and a 2024 review of high-strain composites for deployable structures that treats long-term stowage, stress relaxation and accumulated plastic strain as central concerns.

Crease mechanics is likewise an active field, including measured moment-angle laws for plastic creases, procedures producing repeatable residual fold angles under controlled force, viscoelastic growth of crease equilibrium angles over time, and recent work finding crease angle decreasing progressively with folding cycles.

4. The gap that survives

Set the welded case beside the packaged one and the difference is not in whether the phenomenon is known. It is in what exists downstream of knowing.

	WELDED METALLIC CYLINDER	FOLDED / STOWED DEPLOYABLE
Imperfection located by design	yes	yes
Measured on flight-representative articles	yes, routinely	isolated cases
Published signature, decomposed	yes	none found
Imperfection data bank	yes	none
Validated against full-scale test	yes	one single-specimen pair
Design factor in service	yes, on SLS	none; proposed for booms
Named as an imperfection source in SP-8007 Rev 2 or ECSS-E-HB-32-24A	yes	no

The narrowed claim this note makes is the last two rows, and only those: **no systematic data set, published imperfection signature or design guideline exists for packaging-induced imperfections in compression-loaded deployable shells, and neither the current NASA nor the current ECSS buckling document treats folding or stowage as an imperfection source.** That is a claim about the state of published practice, and a single document the author has not found would narrow it further.

5. Why a packaging signature is a different kind of object

The gap has a cause, and it is the part of this subject the author believes is not written down anywhere.

A manufacturing signature is a property of the design and its production route. Measure a weld land once on a representative article and you have characterised it for that concept. It does not change between measurement and flight. The whole apparatus — signatures, data banks, derived knockdown factors — rests quietly on that.

A packaging signature does not have that property. The evidence in section 3 shows it varying along three axes that have nothing to do with the design:

Fold count. The ISAT result — severe strength loss in the first few cycles, then rapidly decreasing effect — means the article's imperfection depends on how many times it has been packaged. A qualification programme folds and unfolds many times before flight. The article that flies is not the article that was characterised unless the cycle count matches.

Stowage duration. The creep literature is unambiguous that stowed deployables relax, and that deployment behaviour varies predictably with stowage time. DLR's 20-year projection is a design-life statement about an imperfection that grows after the drawing is frozen.

Temperature history. The same literature makes relaxation temperature-dependent, and the thermal environment between integration and deployment is mission-specific, not design-specific.

Add the coupling that a geometric signature cannot carry at all: at a crease the material has yielded, so the imperfection arrives with a local stiffness change and possible damage. The two-orders-of-magnitude effective-modulus reduction reported for creased membranes is not a shape; it is a constitutive change at the same location.

A signature that is a function of the article's history rather than of its design cannot be stored as one shape in a data bank. It has to be stored as a family indexed by cycles, time and temperature — or measured on the flight article in its flight state, which for a stowed structure is the thing you cannot do. That is a genuinely different problem from the welded case, and it is why borrowing the existing apparatus unmodified does not close it.

6. What a characterisation programme would have to produce

Not a knockdown factor. A family.

The deployed field, measured against ideal geometry, at a resolution that resolves crease regions rather than averaging across them.

Its evolution with fold count, through at least the qualification cycle count, so that the saturation the ISAT programme observed is quantified rather than assumed.

Its dependence on stowage duration and temperature, over intervals representative of the mission, so that the article's history enters the model as a variable.

A crease constitutive model, not only a geometry. Residual angle, local stiffness reduction and damage, since the geometric field alone demonstrably does not carry the effect.

Nonlinear analysis on the measured geometry, with modal projection used as a screening diagnostic rather than as the answer. Koiter's result is first-order and holds cleanly for well-separated modes; axially compressed cylinders have densely clustered eigenvalues, and a line-localised feature such as a crease has broadband modal content and interacts with many modes at once. Projection tells you where to look. It does not tell you the answer.

A statement of what the programme did not cover.

7. Where this matters, and where it does not

It matters for compression-loaded deployables: booms, masts, rigidizable inflatable tubes, and the local crippling and flange buckling modes of thin-shell boom sections. This is where the measured evidence of post-packaging strength loss sits, and where the stowage-creep work is concentrated.

It largely does not matter for pressurised softgoods habitats. In an expandable habitat the restraint layer is the primary structural element and internal pressure places it in tension; the governing concerns are creep rupture, seams, load uniformity and a factor of safety of 4.0 on the restraint layer, not compressive buckling. Fold-induced imperfection is a real question for such structures, but it is a question about strength and creep of a tension member, not about buckling knockdown. A reader working on an expandable habitat should take section 5's argument as applying to their *rigid* elements and to launch and depressurised configurations, if at all.

And the practice this note describes is not a practice this note has observed. The author has found no evidence that anyone applies SP-8007 knockdown factors to folded deployables. Boom work is generally handled as beam-column analysis with a deterministic initial imperfection, which is a reasonable method. The argument here is not that the sector is doing something wrong; it is that the input the method needs has not been characterised, and that where it has been reached for, as in the Langley boom work, it has had to be invented locally.

8. A terrestrial precedent, and its limits

The author's doctoral work is one worked instance of measured-imperfection verification against a destructive test, offered here for the shape of the method rather than for its numbers.

Three steel plate girders with Class 4 webs were fabricated to drawing and surveyed before loading. The web of the first was measured on a grid of 34 levels of 15 points — 510 points against the ideal plane — with a maximum deviation of 4.43 mm against a 4.16 mm fabrication tolerance, so the article was 6 percent out of specification and the analysis knew by how much. The measured field was carried into the model by superposition of buckling eigenmodes. Predicted first yield agreed with test to within 1.0, 8.5 and 13 percent across the three articles. Theory placed the maximum out-of-plane displacement at 36.7 percent of web height under pure bending; measurement found it at 34.2 percent.

The last figure is the one that bears on section 6. If the governing question is where an imperfection sits relative to a mode, the method must be one that predicts location, not only load.

What does not transfer. Steel, flat plates, monotonic static loading to collapse, room temperature, one gravity, and a single measurement of an imperfection that did not change between survey and test. No folding, no cycling, no stowage interval, no vacuum, no thermal history, no pressure vessel, no crease. The precedent establishes that measured-imperfection verification works where the imperfection is static. Section 5 is an argument that the deployable case is harder precisely because it is not.

9. What this note does not support

It is a review and a position, not a result. No folded article was analysed, measured or tested for this note.

The gap claim is narrowed and still an absence claim. Section 4 asserts that no systematic data set, published signature or design guideline exists, and that the two current buckling documents do not name folding as an imperfection source. That rests on what the author has found. A published data set, a company's internal characterisation, or a clause in a document not reviewed would each narrow or refute it, and the author would want to know of any.

An earlier draft of this note was wrong in three ways, recorded here because the corrections are load-bearing. It asserted that the shell-buckling and folded-structure literatures had not been joined, which section 3 refutes. It presented the inadequacy of a scalar factor for a located imperfection as a new argument, when it is standard and codified. And it described SP-8007's knockdown factor as a statistical lower bound, when it is a lower-bound envelope fitted to test data and carries no stated coverage probability. That earlier draft was not issued.

Section 5 is argued, not measured. That a packaging signature varies with fold count, stowage duration and temperature follows from the cited work on each axis separately. No study known to the author has measured all three on one flight-relevant article, and the magnitudes matter: if the variation is small, the existing apparatus absorbs it and this note is of little consequence.

The modal-projection screening in section 6 inherits Koiter's limits, as that section states. For clustered modes it is a diagnostic and not a prediction.

Currency. SP-8007 Revision 2 dates from 2020 and the ECSS handbook from 2010; NESC has stated that revised buckling guidelines are forthcoming. Anything here about the state of published practice should be checked against current issues before being relied upon.

10. Sources

NASA/SP-8007-2020/REV 2, *Buckling of Thin-Walled Circular Cylinders*, November 2020. Source of the analysis-based design approach, the imperfection-signature definition, the weld-land Fourier decomposition, and the statement that the lower-bound factors derive from outdated manufacturing processes.

NASA Engineering and Safety Center, *Buckling Knockdown Factors*, NESC Technical Bulletin No. 16-01, June 2016. Source of "most widely used source of KDFs", the caution against a universal 0.65 composite factor, and the statement that revised guidelines are forthcoming.

NASA-STD-5001B with Change 3, October 2022. §4.5 requires analyses of thin-walled shell structures to account for differences between idealised model geometry and the physical structure; §4.5.4 requires buckling evaluation to address creep.

ECSS-E-HB-32-24A, *Buckling of Structures*, 24 March 2010. Realistic, worst-case and stimulating imperfections; manufacturing signatures; Imperfection Data Bank; measured imperfections. Advisory, not normative.

W. T. Koiter, *On the Stability of Elastic Equilibrium*, 1945. Mode-affine imperfections and first-order imperfection sensitivity.

J. W. Hutchinson, on the empirical character of knockdown factors and their lack of theoretical significance.

A. Barker and S. D. Guest, *Inflatable Triangulated Cylinders*, IUTAM-IASS Symposium on Deployable Structures, 2000. Folded-versus-virgin buckling comparison; buckling initiating at valley folds. Single specimen pair.

R. E. Freeland et al., *Inflatable Space Antenna Technology (ISAT)*, IAC-04-IAF-I.1.10, 2004. Compressive strength loss after packaging cycles, saturating with cycle count.

G. Greschik and M. M. Mikulas, *On Imperfections and Stowage Creases in Aluminum-Rigidized Inflated Cylinders*, AIAA-96-1332, 1996.

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J. M. Fernandez, *Advanced Deployable Shell-Based Composite Booms for Small Satellite Structural Applications Including Solar Sails*, NASA Langley, 2017. Stowage flattening limits and the proposal of a boom buckling knockdown factor.

J. Salazar and J. M. Fernandez, AIAA SciTech 2021, on buckling-load reduction from prolonged stowage.

NASA, *Structural Architectures for Self-Erecting Lunar Towers*, AIAA SciTech 2023. Stowage-induced creep curvature used as the initial imperfection in beam-column buckling analysis.

M. Meyer, M. Hillebrandt and C. Hühne, DLR, ECSSMET 2021, on long-term relaxation of deployable booms.

Kwok and Pellegrino on viscoelastic tape springs; Brinkmeyer et al. on long-term stowage; *Design, modeling, and manufacturing of high strain composites for space deployable structures*, Communications Engineering, 2024, on long-term stowage effects, stress relaxation and accumulated plastic strain.

Dharmadasa and López Jiménez on plastic crease moment-angle behaviour and repeatable residual fold angles.

M. W. Kasiak, *Stateczność środków zginanych stref blachownic w świetle teorii, norm, analiz numerycznych i eksperymentalnych*, doctoral dissertation, Gdańsk University of Technology, Faculty of Civil and Environmental Engineering, 2015. Supervisor: K. Żółtowski. Source of the measured-imperfection programme in section 8. PN-97/B-06200 is the source of the 4.16 mm web flatness tolerance.

PSE-TM-03 and PSE-TM-04, postsingularity.engineer.

Tools. No analysis was performed for this note. The girder work in section 8 used SOFiSTiK on a personally held licence, with QUAD4 shell elements.

Method note. The first draft of this note was checked against the literature before issue, and three of its central claims did not survive that check. Section 9 records what they were.