

How Much Damage Does the Stretch-Dominated Advantage Survive? Topology Selection for Lattice Structures Under Realistic Imperfections

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ABSTRACT

Stretch-dominated lattices such as the octet truss are preferred over bending-dominated architectures such as the body-centred cubic cell because their stiffness scales linearly with relative density rather than quadratically. The comparison is usually made for the ideal geometry. Manufactured lattices contain strut thickness variation, waviness and missing members, and the two topology classes do not tolerate those defects equally: a stretch-dominated lattice carries load through determinate paths, while a bending-dominated one is highly redundant. This study quantifies the stiffness and strength advantage of stretch-dominated topology across relative density, identifies where strut buckling rather than yielding governs collapse, and determines how much strut loss the advantage survives. Analytical Gibson–Ashby scaling relations were evaluated for both topology classes in an aluminium alloy of 70 GPa modulus and 250 MPa strut yield stress, across relative densities from 0.02 to 0.35. Collapse strength for the stretch-dominated lattice was taken as the lesser of strut yielding and elastic strut buckling, with the buckling coefficient calibrated so that the two coincide near a relative density of 0.05. Imperfection sensitivity was evaluated by Monte Carlo over populations of 4,000 struts with log-normal thickness variation and a randomly removed fraction, treating the stretch-dominated response as governed by the weakest members of a critical load path and the bending-dominated response as governed by the surviving population mean. The stiffness advantage of stretch-dominated topology fell from 11.3-fold at a relative density of 0.03 to 1.1-fold at 0.30, so the architectural choice matters most precisely where lattices are lightest. Strut buckling governed stretch-dominated collapse below a relative density of 0.050, reducing strength at 0.03 from 2.46 MPa under a yielding assumption to 1.45 MPa, a 41 % overestimate if buckling is ignored. Imperfection sensitivity was markedly asymmetric: with 15 % strut thickness variation and 5 % of struts missing, the knockdown factor was 0.606 for the stretch-dominated lattice and 0.975 for the bending-dominated one. The strength advantage nevertheless persisted over a wide range, falling from 2.42 to 1.96 at a relative density of 0.10 as strut loss rose from zero to 10 %, and reversing only at 36 % strut loss. At a relative density of 0.25 the reversal occurred at 20 %. Stretch-dominated topology remains the correct default, but its margin is smaller than ideal-geometry comparisons imply and shrinks with both increasing density and increasing defect content. Two design rules follow: check strut buckling explicitly below a relative density of about 0.05, and prefer bending-dominated architecture where process control is poor or where damage tolerance rather than initial stiffness governs.

Keywords: lattice structures; cellular materials; stretch-dominated topology; strut buckling; imperfection sensitivity; additive manufacturing.

1. INTRODUCTION

The mechanical behaviour of a lattice depends less on what it is made of than on how its members carry load. Maxwell's criterion distinguishes architectures in which the struts are loaded predominantly in tension and compression from those in which they bend, and the distinction produces a difference in scaling that is the central result of cellular solids theory: the effective modulus of a stretch-dominated lattice rises in proportion to relative density, while that of a bending-dominated lattice rises with its square [1,2,4].

At low relative density that difference is large, and it is the reason the octet truss and its relatives dominate the lattice design literature and most commercial lattice software [3,5-7,18]. The argument is sound and is made almost universally for the ideal geometry.

Manufactured lattices are not ideal. Struts produced by powder-bed fusion vary in effective load-bearing cross-section because of partially melted surface powder, they deviate from straightness, and some are missing or unbonded altogether, particularly at shallow build angles [8-10,12]. These defects do not affect the two topology classes equally, and the reason is structural rather than metallurgical. A stretch-dominated lattice approaches static determinacy: its struts form a load path with limited alternative routes, so a member that is thin, wavy or absent is not readily compensated. A bending-dominated lattice is highly redundant, and load sheds to neighbours.

Two further issues complicate the ideal comparison. Slender struts in a lightweight stretch-dominated lattice may buckle elastically before they yield, which caps strength at low density in a way the yield-based scaling does not capture [15]. And the stiffness advantage itself is density dependent, shrinking as relative density rises.

This study quantifies all three effects on a common basis and asks a design question: given a manufacturing process of known defect content, at what point does the stretch-dominated advantage disappear?

2. MODEL

2.1 Scaling Relations

Effective properties are expressed through relative density $\bar{\rho}$, the fraction of the unit cell occupied by solid. For the stretch-dominated class the standard relations are [1,3]

$$\frac{E^i}{E_s} \approx \left(\frac{1}{3}\right) \bar{\rho}, \frac{\sigma^i}{\sigma_{ys}} \approx \left(\frac{1}{3}\right) \bar{\rho} \quad (1)$$

and for the bending-dominated class [1,2]

$$\frac{E^i}{E_s} \approx C_1 \bar{\rho}^{-2}, \frac{\sigma^i}{\sigma_{ys}} \approx C_2 \bar{\rho}^{-3/2} \quad (2)$$

with $C_1 \approx 1.0$ and $C_2 \approx 0.3$. The quadratic stiffness exponent and the three-halves strength exponent are the signature of bending-governed deformation and plastic hinge formation respectively.

Stretch-dominated collapse can also occur by elastic buckling of the compressive struts, for which the cellular scaling is quadratic in relative density [1,15]:

$$\sigma_{buckling} = k_b E_s \bar{\rho}^{-2} \quad (3)$$

The coefficient k_b depends on strut slenderness and end restraint. It was calibrated here so that buckling and yielding coincide at $\bar{\rho} = 0.05$, giving $k_b = 0.0238$, which places the transition in the range reported for slender-strut lattices [3]. Collapse strength is taken as the lesser of Equations (1) and (3). The model parameters are listed in Table 1.

Table 1: Model parameters.

Parameter	Value	Basis
Strut modulus, E_s	70 GPa	Aluminium alloy
Strut yield stress, σ_{ys}	250 MPa	Aluminium alloy
Stretch-dominated coefficients	1/3 for both stiffness and strength	Standard octet-type relations
Bending-dominated coefficients	$C_1 = 1.0$, $C_2 = 0.3$	Standard Gibson–Ashby values
Buckling coefficient, k_b	0.0238	Calibrated to place the transition at $\bar{\rho} = 0.05$
Relative density range	0.02 to 0.35	Practical lattice range
Struts per Monte Carlo realisation	4,000	Representative of a component-scale lattice
Strut thickness variation	Log-normal, CV 5 % or 15 %	Representative of powder-bed fusion
Missing strut fraction	0 to 30 %	Spans good to poor process control

Note: All values are representative assumptions rather than measurements. Absolute stresses are illustrative; the comparisons between topology classes follow from the scaling exponents and are insensitive to the material constants.

2.2 Imperfection Model

Each realisation draws 4,000 strut strengths from a log-normal distribution of unit median with the stated coefficient of variation, then removes a random fraction. The two topology classes are then treated differently, and the difference is the modelling assumption on which the imperfection results rest [13,14].

Stretch-dominated. Collapse is taken to be governed by the weakest members of a critical load path, represented as the mean of the weakest 2 % of surviving struts, with a further penalty of $(1 - f)^{2.5}$ for the loss of load paths. This represents near-determinate behaviour in which a small number of highly loaded members control collapse and removing members disrupts the truss action itself.

Bending-dominated. Collapse is taken to be governed by the mean of the surviving population with a mild penalty of $(1 - f)^{0.5}$, representing redundancy in which load sheds to neighbouring cells.

These are idealisations at the two ends of a spectrum and are stated as such. A real lattice of either class lies between them, and the exponents chosen set the magnitude of the asymmetry rather than deriving it; Section 4.3 discusses what a finite element treatment would be expected to change.

3. RESULTS

3.1 The Stiffness Advantage Is Density Dependent

Figure 1 and Table 2 give the effective properties of the two topology classes across relative density.

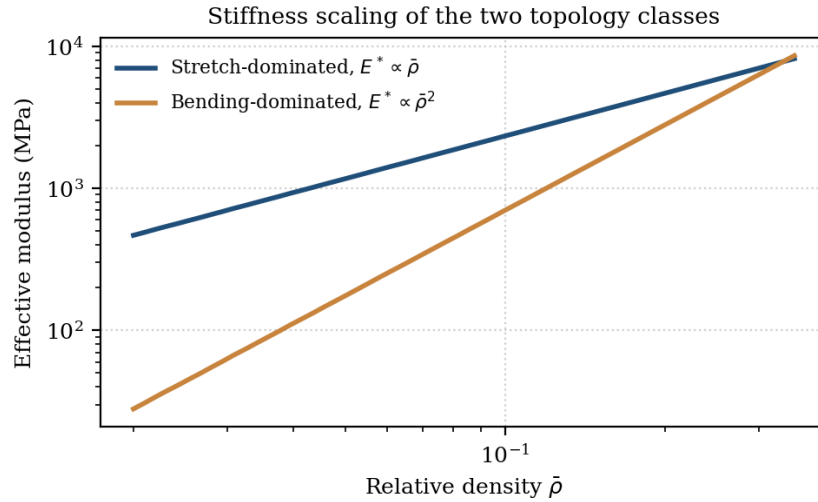


Fig.1: Effective modulus against relative density for the two topology classes, on logarithmic axes.

Table 2: Effective properties by relative density.

$\bar{\rho}$	E^* , stretch (MPa)	E^* , bending (MPa)	Stiffness ratio	σ^* , stretch (MPa)	σ^* , bending (MPa)	Governing mode
0.03	687.9	60.8	11.3	1.45	0.38	Buckling
0.05	1,173.0	176.9	6.6	4.19	0.85	Yielding
0.10	2,313.5	688.1	3.4	8.26	2.34	Yielding
0.20	4,562.7	2,676.6	1.7	16.30	6.49	Yielding
0.30	7,060.6	6,409.5	1.1	25.22	12.48	Yielding

The stiffness ratio falls from 11.3 at a relative density of 0.03 to 1.1 at 0.30. This is not a defect of either architecture but a direct consequence of the differing exponents: the ratio of a linear to a quadratic scaling is itself inversely proportional to density.

The engineering consequence is that topology selection is a high-stakes decision for very light lattices and nearly irrelevant for dense ones. At a relative density of 0.30 a designer choosing between an octet and a body-centred cubic cell is choosing between structures that differ by 10 % in stiffness, a margin easily outweighed by manufacturability, inspectability or thermal considerations.

3.2 Where Buckling Takes Over

Figure 2 shows the yielding and buckling branches of collapse strength for the stretch-dominated lattice.

Strut buckling governs stretch-dominated collapse below a relative density of 0.050. Above that the struts are stocky enough to yield first and the linear strength scaling applies; below it, strength follows the quadratic buckling branch and falls away faster than the yield-based relation predicts.

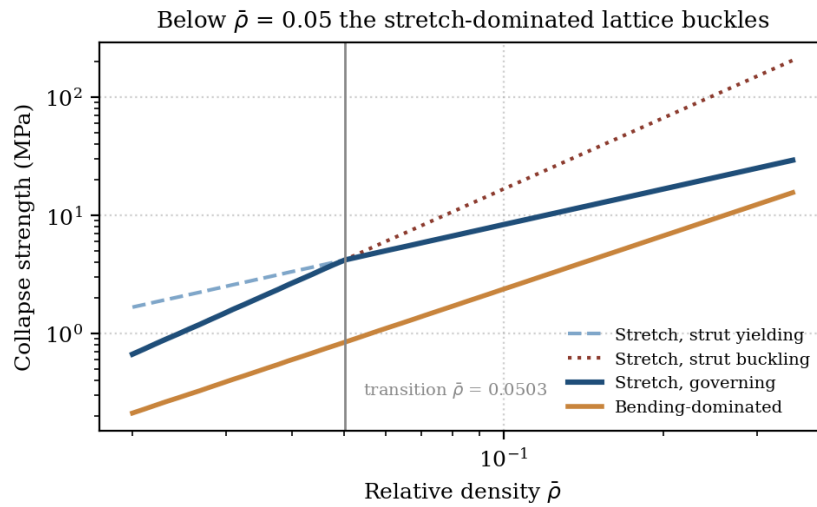


Fig.2: Collapse strength against relative density, showing the yielding and buckling branches for the stretch-dominated lattice.

The magnitude matters for design. At a relative density of 0.03 the yield-based relation gives 2.46 MPa and the buckling-limited value is 1.45 MPa — a 41 % overestimate for a designer who applies the linear scaling without checking. That error occurs precisely in the density range where stretch-dominated topology is most attractive on stiffness grounds, so the two effects work against each other: the architecture is chosen for a low-density application and then fails at a load the selection calculation did not anticipate.

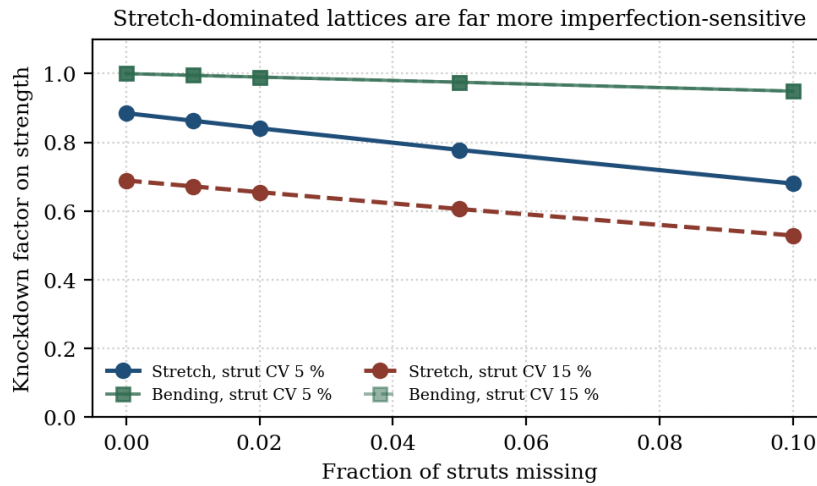


Fig.3: Knockdown factor against the fraction of struts missing, for two levels of strut thickness variation.

The transition density is not universal. It depends on strut slenderness and end restraint through the buckling coefficient, and on the ratio of yield stress to modulus for the parent material [16]. A higher-strength alloy at the same modulus pushes the transition to higher density, because the struts must be stockier before yielding precedes buckling — so the problem is worse, not better, for high-strength materials.

3.3 Imperfection Sensitivity

Table 3 and Figure 3 give the knockdown factors on collapse strength for both topology classes.

The asymmetry is large and appears even with no struts missing at all. Strut thickness variation of 15 % alone reduces stretch-dominated strength by 31 % while leaving the bending-dominated lattice essentially unaffected, because the former is governed by the weakest members of a load path and the latter by the population mean [8,9].

Table 3: Knockdown factors on collapse strength.

Struts missing	Strut CV	Stretch-dominated	Bending-dominated	Ratio of knockdowns
0 %	5 %	0.885	1.000	0.89
0 %	15 %	0.689	1.000	0.69
1 %	15 %	0.672	0.995	0.68
2 %	15 %	0.655	0.990	0.66
5 %	5 %	0.778	0.975	0.80
5 %	15 %	0.606	0.975	0.62
10 %	15 %	0.529	0.949	0.56

Adding strut loss widens the gap. With 5 % of struts missing and 15 % thickness variation — a combination that would not be regarded as an unusually poor build — the stretch-dominated knockdown is 0.606 against 0.975. Two fifths of the nominal strength has gone, and the designer who sized the part from ideal-geometry relations has no margin for it unless it was applied explicitly.

The dependence on thickness variation is worth separating from the dependence on strut loss, because they are controlled by different process levers. Thickness variation responds to parameter optimisation, powder quality and post-process surface treatment; strut loss responds to build orientation, support strategy and minimum feature size. On these results the stretch-dominated lattice is more sensitive to both, but the CV effect is the larger of the two at realistic defect levels.

3.4 How Much Damage the Advantage Survives

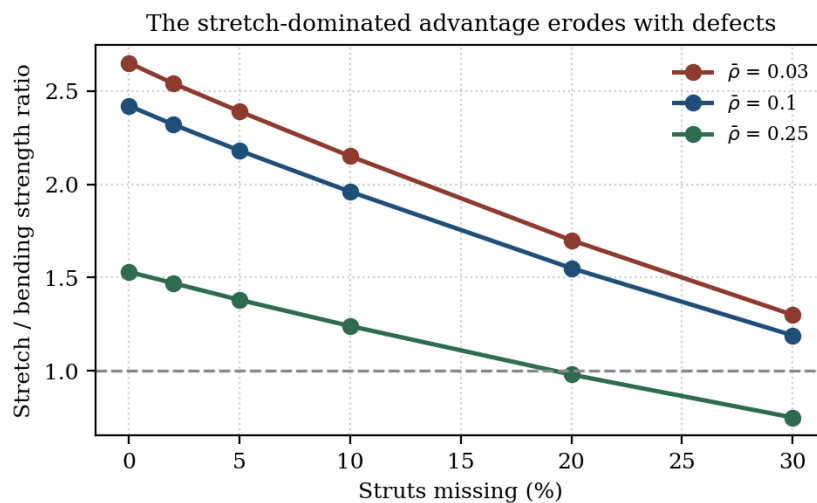


Fig.4: Ratio of stretch-dominated to bending-dominated collapse strength against strut loss.

Table 4 and Figure 4 give the ratio of stretch-dominated to bending-dominated collapse strength as strut loss increases.

Table 4: Strength ratio of stretch-dominated to bending-dominated topology.

Struts missing	$\bar{\rho} = 0.03$	$\bar{\rho} = 0.10$	$\bar{\rho} = 0.25$
0 %	2.65	2.42	1.53
2 %	2.54	2.32	1.47
5 %	2.39	2.18	1.38
10 %	2.15	1.96	1.24
20 %	1.70	1.55	0.98
30 %	1.30	1.19	0.75

The stretch-dominated lattice remains stronger over most of the range examined, which is the honest answer and is worth stating before the qualification. At a relative density of 0.10 it retains a 1.96-fold advantage with a tenth of its struts missing, and the advantage does not reverse until 36 % strut loss — a level of damage at which the structure has other problems. Table 5 and Figure 5 give the strut loss at which the bending-dominated lattice becomes the stronger choice.

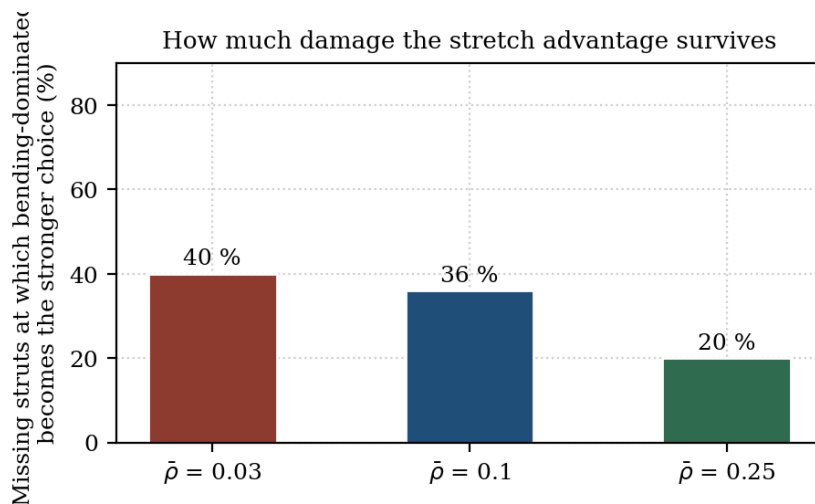


Fig.5: Strut loss at which the bending-dominated lattice becomes the stronger choice.

Table 5: Critical strut loss for reversal.

Relative density	Strut loss at reversal	Advantage at zero defects
0.03	40 %	2.65
0.10	36 %	2.42
0.25	20 %	1.53

The critical strut loss falls with density, from 40 % at a relative density of 0.03 to 20 % at 0.25, because the ideal-geometry advantage that has to be eroded is itself smaller at high density. A dense lattice made by a poorly controlled process is therefore the case in which bending-dominated topology becomes genuinely preferable on strength, and it is also the case in which the stretch-dominated stiffness advantage is smallest.

For most engineering practice the message is not that the default should change. It is that the design margin is not what ideal-geometry selection implies: at 5 % strut loss and 15 % thickness variation the advantage at a relative density of 0.10 is 2.18 rather than 2.42 on strength, and the absolute strength is 39 % below nominal. A part sized on nominal properties and built with that defect content is operating on the margin rather than on the design.

4. DISCUSSION

4.1 Principal Findings

Four results follow. The stiffness advantage of stretch-dominated topology is strongly density dependent, falling from 11.3-fold at a relative density of 0.03 to 1.1-fold at 0.30. Strut buckling governs stretch-dominated collapse below a relative density of 0.050, where the yield-based relation overestimates strength by 41 % at 0.03. Imperfection sensitivity is markedly asymmetric, with knockdowns of 0.606 against 0.975 at 15 % thickness variation and 5 % strut loss. And the strength advantage nonetheless survives substantial damage, reversing only at 36 % strut loss at a relative density of 0.10 and 20 % at 0.25.

4.2 Design Implications

Table 6 summarises each finding, its implication and the corresponding design rule.

Table 6: Implications.

Finding	Implication	Design rule
Stiffness ratio falls from 11.3 to 1.1 with density	Topology matters most for the lightest lattices	Above $\bar{\rho} \approx 0.25$, select on manufacturability rather than architecture
Buckling governs below $\bar{\rho} = 0.05$	Linear strength scaling is unsafe there	Check strut buckling explicitly below $\bar{\rho} \approx 0.05$
Transition rises with material strength	High-strength alloys buckle over a wider range	Recheck the transition when changing alloy, not only geometry
15 % strut CV alone cost 31 % of strength	Thickness variation matters without any strut loss	Measure strut cross-section variability, not just porosity
Knockdown 0.606 against 0.975 at realistic defects	Ideal-geometry properties overstate the stretch case	Apply topology-specific knockdowns, not a single factor
Advantage survived to 36 % strut loss at $\bar{\rho} = 0.10$	Stretch-dominated remains the right default	Do not abandon the architecture on imperfection grounds alone
Reversal at 20 % at $\bar{\rho} = 0.25$	Dense lattices with poor control favour redundancy	Prefer bending-dominated where process control is weak and density is high

The fifth row is the one with the most immediate practical consequence. Lattice design software generally applies scaling relations derived for ideal geometry, and where a knockdown is applied at all it is usually a single factor independent of topology [12]. These results suggest that is the wrong shape of correction: the appropriate knockdown differs by a factor of about 1.6 between the two topology classes at realistic defect levels, so applying a common factor either over-penalises the redundant architecture or under-penalises the determinate one.

The second row is a check rather than a change of approach and costs nothing. Computing the buckling strength from Equation (3) alongside the yield strength, and taking the lesser, requires one additional line in a sizing calculation and prevents a 41 % overestimate in the density range where stretch-dominated lattices are most often used.

4.3 Limitations

The imperfection analysis is the principal limitation. The two topology classes are represented by idealised statistical rules — weakest members of a critical path with a load-path penalty for the stretch case, surviving population mean with a mild penalty for the bending case — rather than by simulation of a structure. The exponents in those penalties are chosen rather than derived, and they set the magnitude of the asymmetry. A finite element study of explicit lattice geometries with randomly perturbed and removed struts would give the correct magnitudes and is the natural next step [8,9,14]; the qualitative asymmetry follows from determinacy and redundancy and would be expected to survive, but the critical strut-loss values in Table 5 should be treated as indicative rather than as design numbers.

Strut waviness is not modelled separately. It reduces buckling capacity more than it reduces yield capacity, so including it would deepen the buckling branch of Figure 2 and move the transition density upward, worsening the stretch-dominated case in exactly the low-density regime identified as vulnerable. Node geometry, stress concentration at joints, and the transition from strut-dominated to node-dominated behaviour at higher densities are likewise absent.

Loading is uniaxial compression and quasi-static. The comparison would differ under multiaxial loading, where stretch-dominated lattices are anisotropic and their advantage is orientation dependent [17]; under fatigue, where defect-initiated cracking rather than collapse governs and the weakest-link argument is stronger still [11]; and under impact, where the bending-dominated architecture's long plateau confers an energy-absorption advantage that this analysis does not represent at all.

Finally, the scaling coefficients are standard values rather than measurements for any specific unit cell, and real octet and body-centred cubic lattices deviate from them. Absolute stresses in Tables 2 to 4 are illustrative and should not be used as design data for any material or cell.

5. CONCLUSION

Stretch-dominated lattices are stiffer than bending-dominated ones by a factor that falls from 11.3 to 1.1 as relative density rises from 0.03 to 0.30, so the architectural choice is consequential only at low density — and at low density the stretch-dominated lattice is governed by strut buckling rather than yielding below a relative density of 0.050, where ignoring buckling overestimates strength by 41 %.

The architecture is also the more fragile of the two. Fifteen per cent strut thickness variation with 5 % of struts missing reduced stretch-dominated strength to 0.606 of nominal against 0.975 for the bending-dominated case. The advantage nonetheless survived to 36 % strut loss at a relative density of 0.10, so the conclusion is not that the default should change but that the margin is smaller than ideal-geometry selection implies and should be sized with topology-specific knockdowns. Where relative density is high and process control is poor, the redundant architecture becomes the stronger choice at 20 % strut loss, and in that corner the stiffness penalty for choosing it is only about a tenth.

DECLARATIONS

Ethical approval. Not applicable. This is a computational study; no human or animal subjects were involved.

Funding. This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Conflicts of interest. The author declares no conflicts of interest, financial or non-financial, in relation to the subject matter of this manuscript.

Materials and product disclaimer. No specific unit cell, alloy, machine or lattice design package is evaluated. Coefficients in Table 1 are standard or calibrated values and absolute stresses are illustrative; they must not be used as design data.

Modelling disclaimer. The imperfection rules described in Section 2.2 are idealisations of determinate and redundant behaviour, not derived from structural analysis. The critical strut-loss values are indicative; see Section 4.3.

Data and code availability. This is a computational study; no experimental or external datasets were used. All results were generated by the analytical and Monte Carlo model described in Section 2, run with a fixed random seed so that every reported value can be reproduced exactly from the parameters listed in Table 1. The code is available from the corresponding author upon reasonable request.

Author's contribution. Dr. Amarjeet is the sole author of this work and was responsible for the conception and design of the study, development of the scaling and imperfection models, the Monte Carlo simulations, interpretation of the results, preparation of the figures and tables, and drafting, revision and final approval of the manuscript. The author is accountable for all aspects of the work.

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