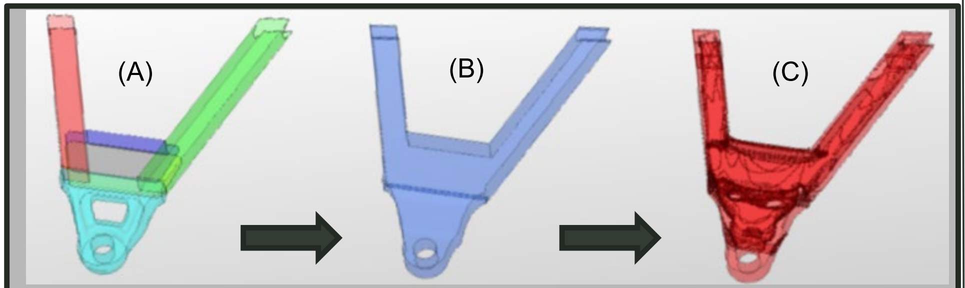
GROUND VEHICLE
SYSTEMS CENTER

Development of a Load-Agnostic Structural Light-Weighting Design Optimization Methodology

Author: Kumar B. Kulkarni

Development of a load-agnostic structural light-weighting design optimization methodology



(A) Five piece weldment (Baseline design)
(B) Design space used for topology optimization
(C) Optimized design (hollowed out area is shown in darker shades)

Innovation

- Ability to perform topology optimization on over-designed subsystems without information on actual service loads
- Internally generated criteria for design constraints based on existing designs
- Multiplicative impact of optimization methodology and Additive Manufacturing of spares/sustainment [4]

Start/finish date: October 1, 2017 – September 30, 2019 (2 year effort)

($M)	PE	Project	FY
0.08 (0.35 FTE)	61101	91A	18
0.08 (0.35 FTE)	61101	91A	19

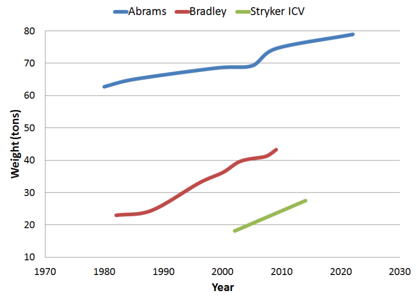
Date: 11/12/2018 POC: Kumar B Kulkarni

Problems/Questions

- Rapid insertion of new technologies needs quick turnarounds in designs of components and sub-systems. These are often over-designed to compensate for lack of good sub-system level performance targets.
- Lack of component-level service loads hampers systematic light-weighting efforts. How to perform a part optimization without the knowledge of service loads?

Theoretical Basis for Research

- Systems are over-designed with large factors of safety, good candidates for weight reduction.
- Topology Optimization methods such as SIMP (Solid Isotropic Material with Penalization)[7,8]
- Mathematical algorithms such as Gradient-based searches/programming



Weight growth in US Army combat vehicles

Relevance to Org Mission

- To improve overall protected and expeditionary mobility utilizing multiple approaches to light-weighting [Value Stream 1, LoE 1.3]
- Supports Army's Lightweight Combat Vehicle S&T Campaign (LCVSTC): Value Stream 3, LoE 3.1, 3.4
- Key enabler to leverage Additive Manufacturing/3D Printing (key Army initiative) for Readiness

Motivation / Prior research

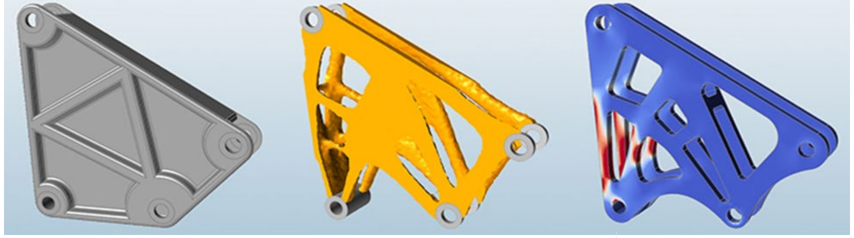
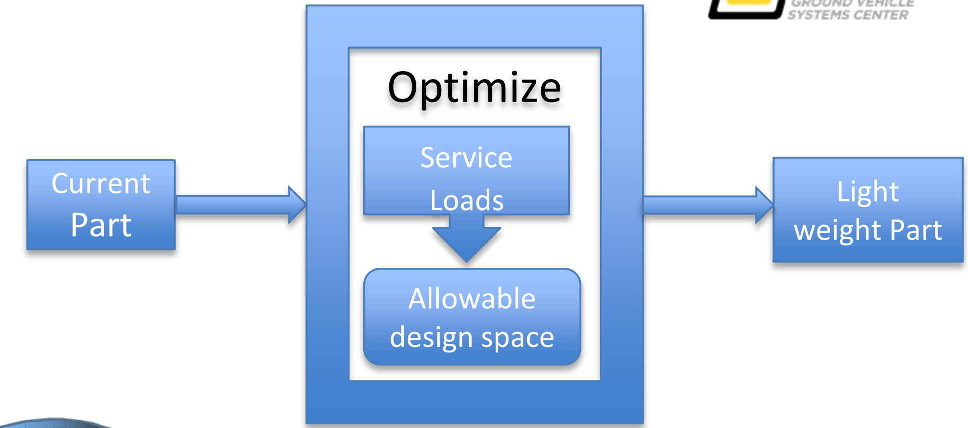


Image Courtesy: Altair's Solid Thinking



Current Part

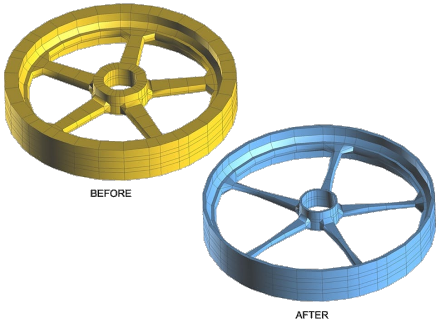
Optimize

Service Loads

Allowable design space

Light weight Part

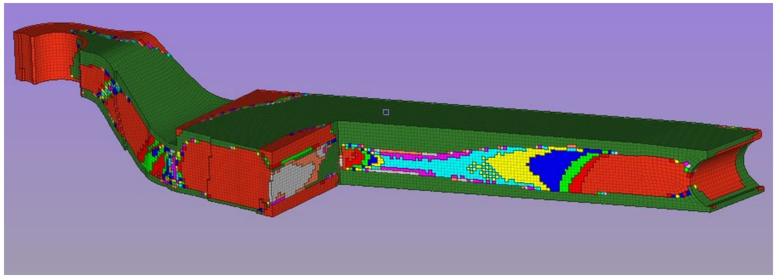
Image Courtesy: Light Rider motorcycle



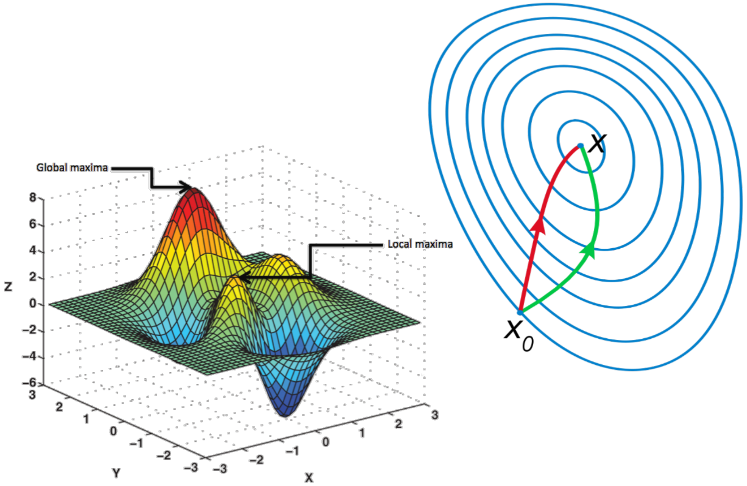
- Extensive research on successful implementation of topology optimization of structures subjected to known service loads[1,2,3,6]
- For military vehicles:
  - Key performance criteria for military vehicles are typically prescribed for a full system. Target cascading methodology to lower levels is not well established (unlike in aerospace industry). Service loads by lower structural components are not readily available.
  - This typically results in over design, adding weight, a significant drawback to Assured Mobility
  - In addition, there is often "dead weight" where the weight does not add any "value"
- Significant efforts are now being dedicated to measuring loads in key components using full vehicle tests, however this takes time and money.
  - Development of a service-load-agnostic method of component design optimization would thus be greatly beneficial, and is a niche research need for the Army.

Overall Technical Approach

- The key strategy of the approach is to use “normalized” design target criteria based on the current baseline component itself, these are:
    - Stiffness: Overall component compliances
    - Strength: Peak von mises stresses to unit loads
    - Other: First few natural frequencies of the global modes of deformation
- There are two potential avenues for weight reduction:
    - Removal of “dead weight” without loss of performance
    - “Significant” weight reductions for “small” accepted reductions in performance; Efficiency = (Δweight / Δperf)
- SIMP method employed[7,8] (Solid Isotropic Material with Penalization for intermediate densities)
    - Finite element-based
    - Material interpolation, Power Law or “density” method
    - Higher the penalization, more the algorithmic penalty for use of non-binary densities
    - Used by most COTS (we use Optistruct®)
- Gradient-based optimization search methods
    - Steepest descent
    - Newton’s method using curvature



SIMP method:
Red (Low Density – remove)
Green (High Density – keep)
Other colors (Intermediate Density – penalty applied)



Gradient “steepest” descent (green) and Newton's method using curvature (red)

Problem Formulation

Topology optimization problem can be written in the general form[7] is stated as;

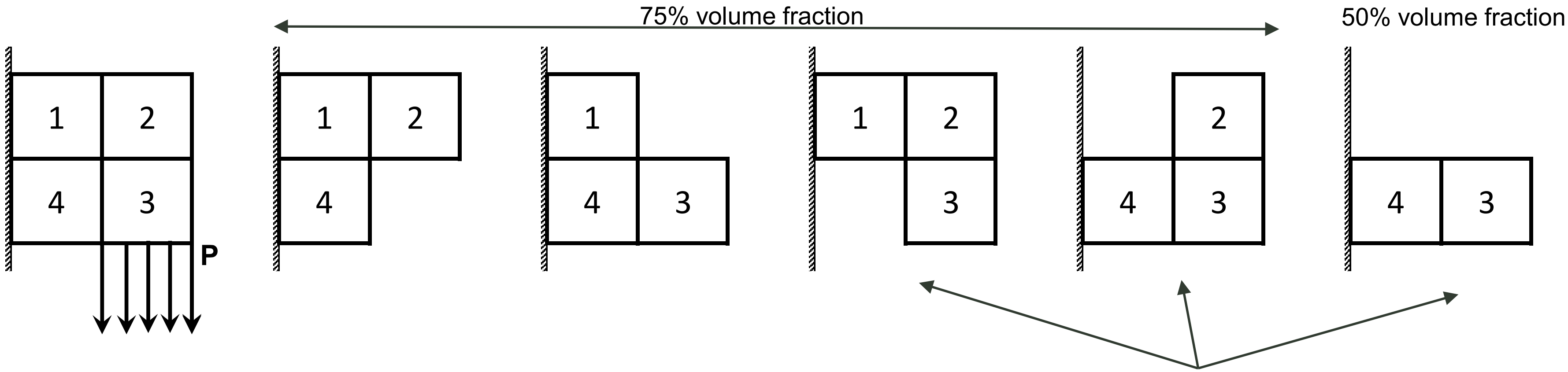
Minimize $\Theta_o(d)$; Subjected to $\Theta_i(d) \le 0$; & $\underline{d}_j \le d_j \le \overline{d}_j$

Where Θ_o is the objective function
Θ_i (for i =1,nc) are the inequality or equality constraints (material responses) that the solution must satisfy
d_j (for j=1,nd) are the design variables (material distribution densities) bounded by $\underline{d}_j$ and $\overline{d}_j$

The structural response is solved using the finite element method within the design domain.

Interpolation of material distribution densities is performed in a continuous manner using the SIMP method which interpolates the material modulus within each discrete element of the design space.

An example of generalized shape optimization involving the optimal distribution of a single material within a given domain[8] is shown below.



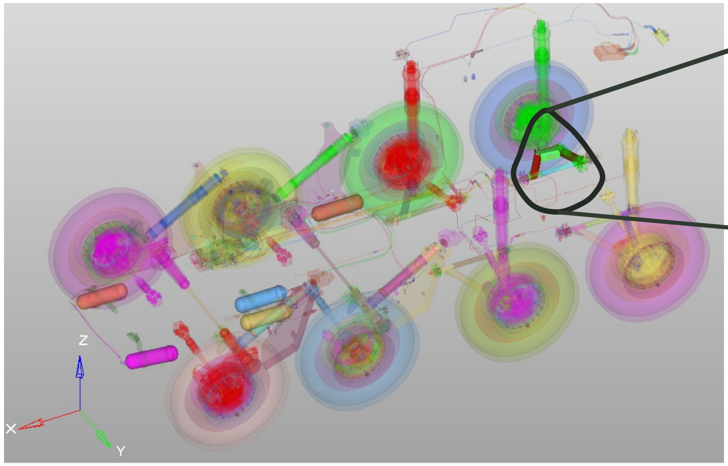
4 finite elements in plane stress, minimize disp @ P

Infeasible, as loading point gets removed

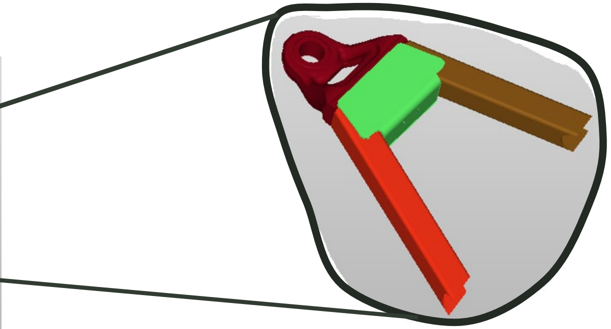
Optimal

Feasible but not optimal

Example: STRYKER Control Arm

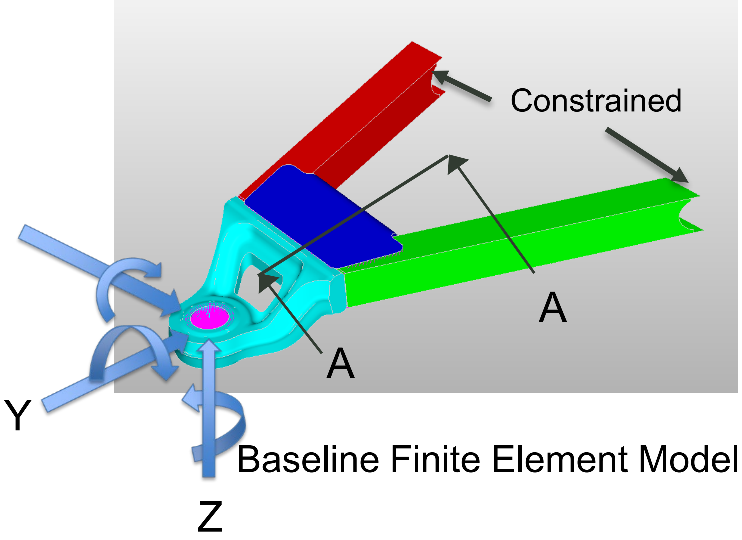


Suspension system of Stryker

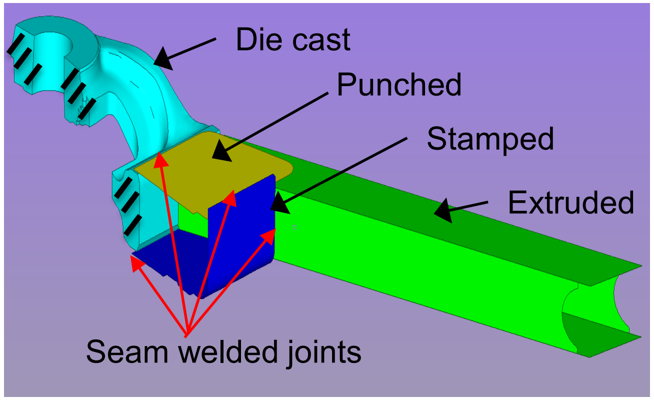


Control arm assembly

Performance targets are set by performing structural analysis using unit loads.



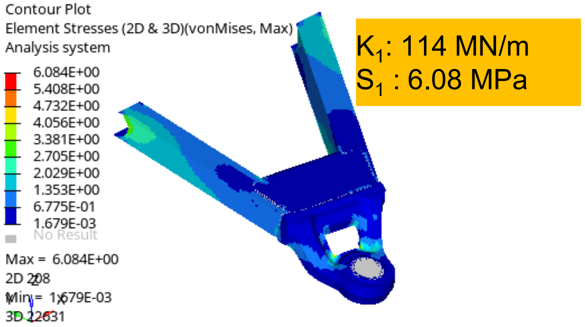
Baseline Finite Element Model



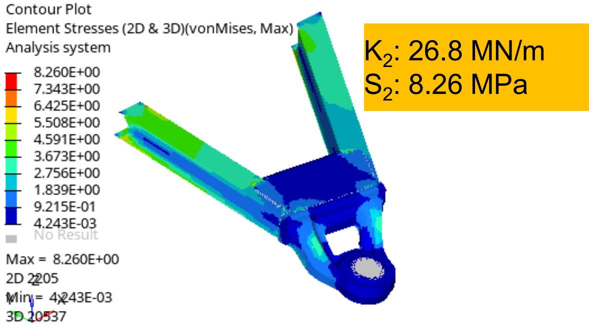
Section AA

Performance targets (Constraints)

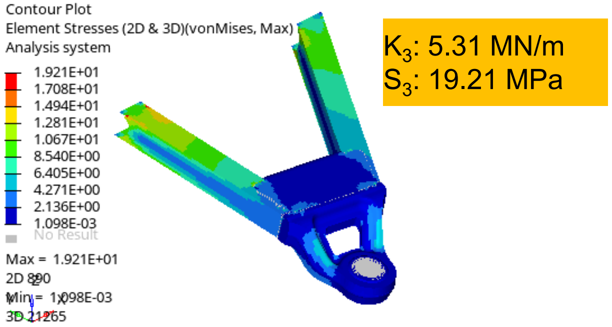
Stiffness and Strength



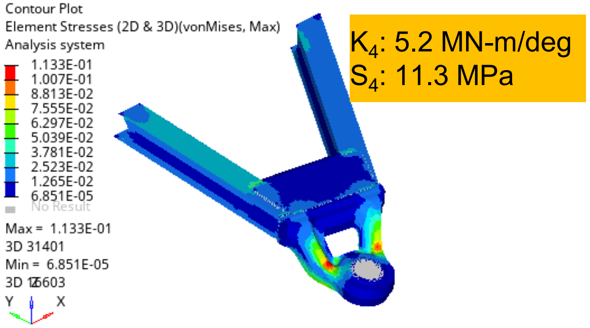
K_1: 114 MN/m
S_1 : 6.08 MPa



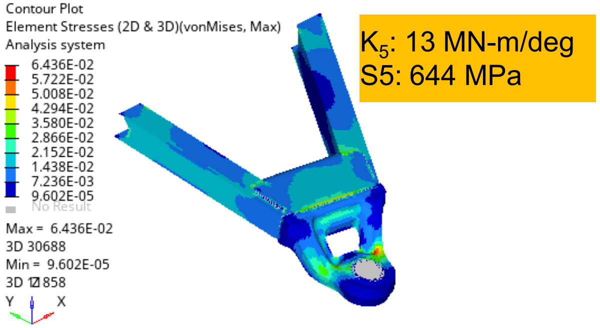
K_2: 26.8 MN/m
S_2: 8.26 MPa



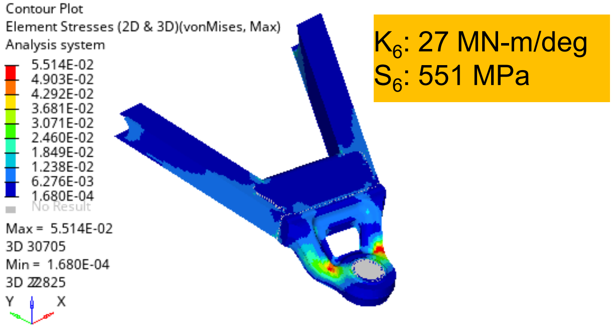
K_3: 5.31 MN/m
S_3: 19.21 MPa



K_4: 5.2 MN-m/deg
S_4: 11.3 MPa

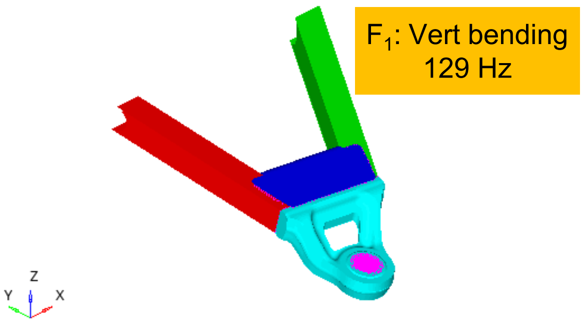


K_5: 13 MN-m/deg
S5: 644 MPa

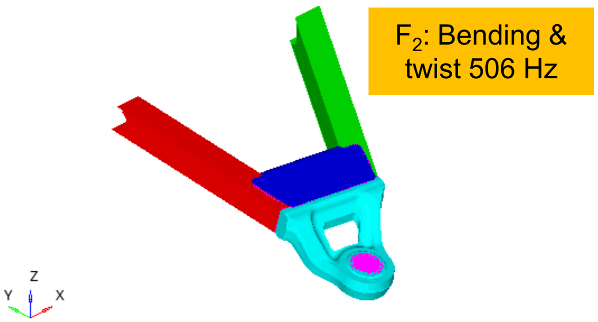


K_6: 27 MN-m/deg
S_6: 551 MPa

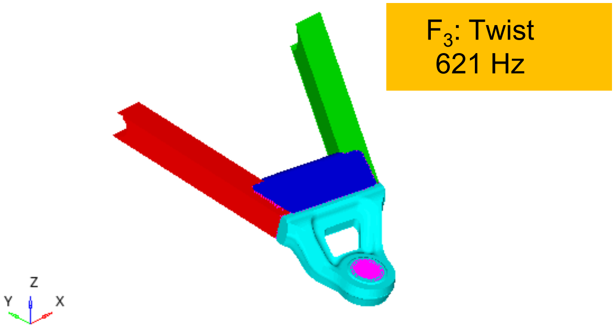
Modal Frequencies



F_1: Vert bending
129 Hz



F_2: Bending &
twist 506 Hz

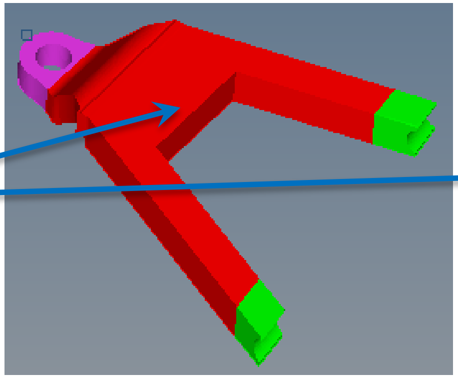


F_3: Twist
621 Hz

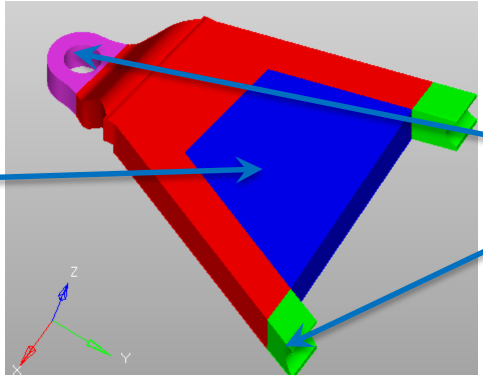
Stiffness (K_i) and vonmises stress (S_i) for i=1..6 in all six directions including the first three natural frequencies, F_j (j=1..3) are set as constraints.

Topology optimization approach

Design Space 1 -
Bounded by the existing package space

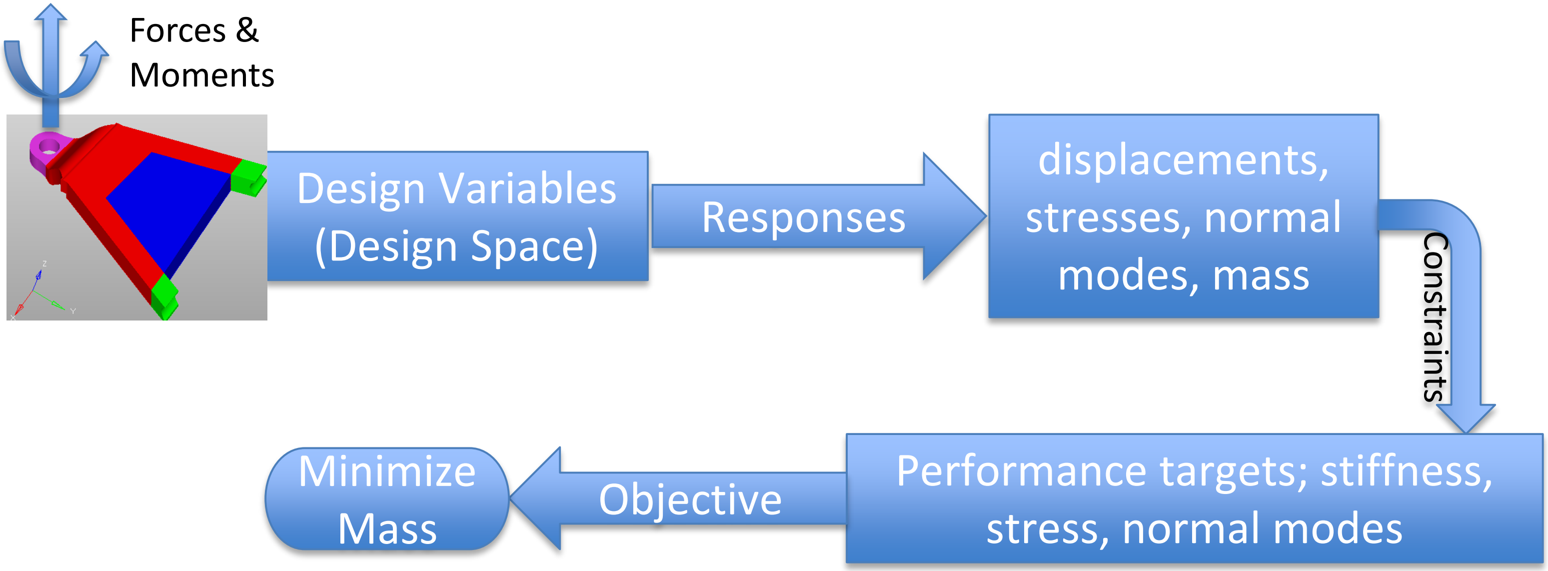


Design Space 2 –
Bounded by the feasible packaging space



Solid block

Optional areas to exclude from the design space to preserve existing mounting/attachment scheme.



Forces & Moments

Design Variables (Design Space)

Responses

displacements, stresses, normal modes, mass

Constraints

Performance targets; stiffness, stress, normal modes

Objective

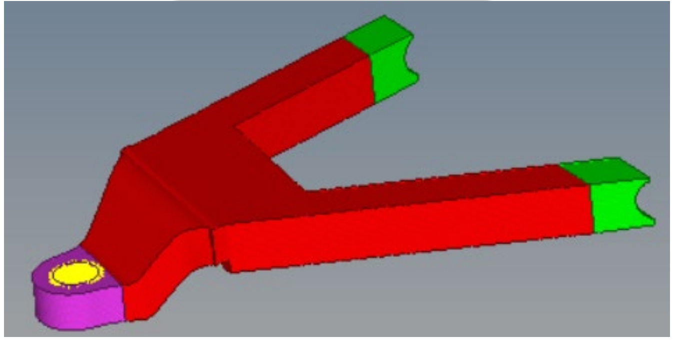
Minimize Mass

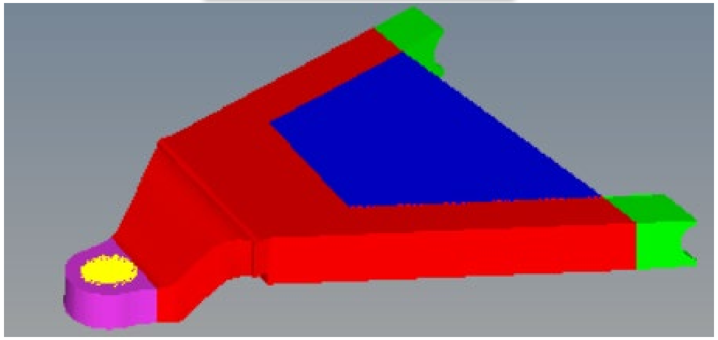
RESULTS: Optimized design space(s)

Design Space 1

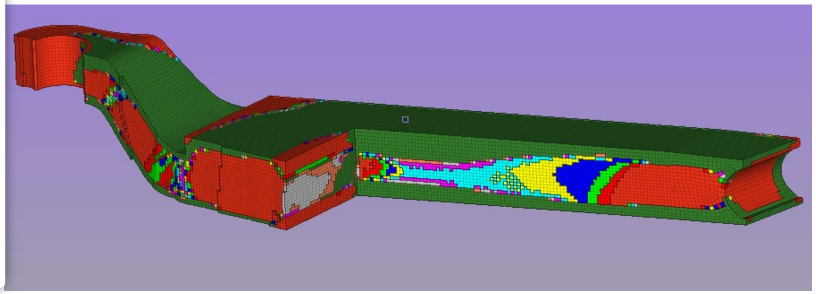
Design Space 2

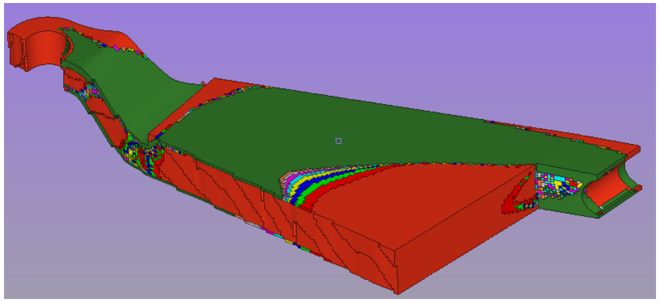
Design Spaces from which optimization is initiated



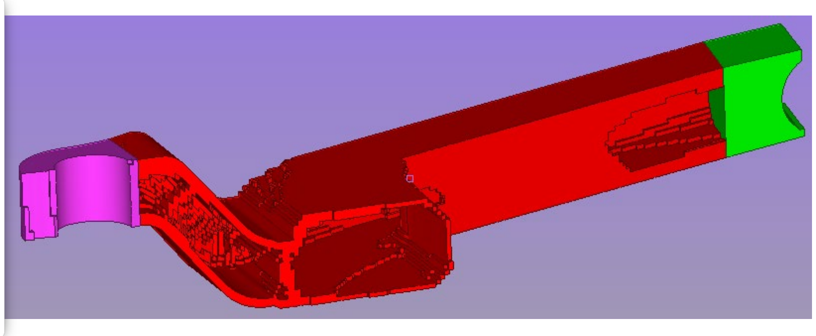


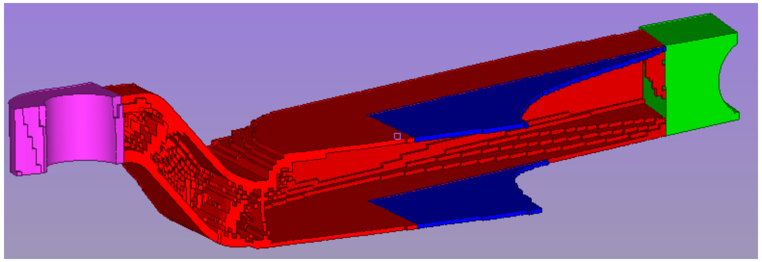
Contours based on element densities. Green>0.9, Red<0.1, other colors intermediate.





“Rough” designs created based on retaining element densities > 0.25. Ends unchanged to maintain assembly interfaces.





Results (FY18)

Response Quantity				Baseline	DS - 1	%Δ	DS - 2	%Δ
1	**Mass, kg**			**18.3**	**17.14**	**7% ▲**	**15.97**	**15% ▲**
2	**Forces**	Compliance, mm/kN	X	8.75E-03	7.97E-03	10% ▲	8.36E-03	5% ▲
3			Y	3.73E-02	3.46E-02	8% ▲	3.59E-02	4% ▲
4			Z	1.88E-01	1.64E-01	15% ▲	1.63E-01	16% ▲
5		Max Von Mises Stress, MPa	X	6.08	4.21	44% ▲	3.89	56% ▲
6			Y	8.26	6.20	33% ▲	6.79	22% ▲
7			Z	19.21	11.91	61% ▲	18.08	6% ▲
8	**Moments**	Compliance, rad/Nm	X	3.39E-06	2.95E-06	15% ▲	3.34E-06	2% ▲
9			Y	1.34E-06	1.19E-06	13% ▲	1.28E-06	5% ▲
10			Z	6.39E-07	5.53E-07	16% ▲	5.69E-07	12% ▲
11		Max Von Mises Stress, MPa	X	1.13E-01	8.23E-02	37% ▲	8.67E-02	30% ▲
12			Y	6.44E-02	5.09E-02	26% ▲	5.04E-02	28% ▲
13			Z	5.51E-02	4.50E-02	23% ▲	4.72E-02	17% ▲
	Natural Frequencies, Hz	Mode Shape	Mode #					
14		Vertical	#1	129	154	16% ▲	168	23% ▲
15		Lateral + twist	#2	506	570	11% ▲	638	21% ▲
16		Lateral + twist out of phase	#3	621	667	7% ▲	744	17% ▲
17		Vertical 2nd order	#4	761	807	6% ▲	802	5% ▲
18		Lateral higher order	#5	1218	1254	3% ▲	1352	10% ▲
19		Complex	#6	1469	1422	-3% ▼	1554	5% ▲

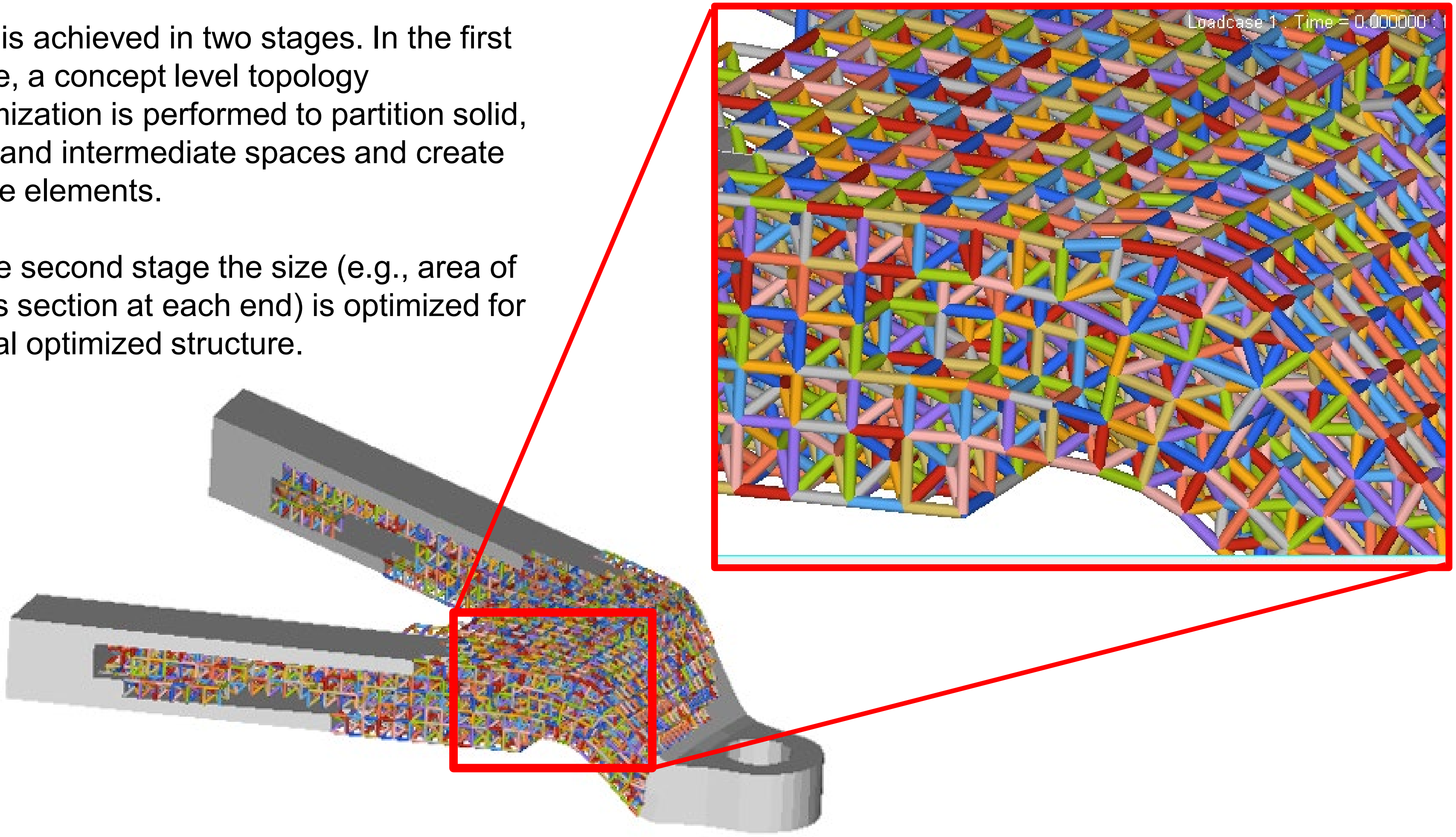
▲	Better. Lower compliance, lower stress, higher modal frequency
▼	Worse. Higher compliance, higher stress, lower modal frequency

Both design spaces met/exceeded an average of
>10% for stiffness; >32% for strength ; >16% for natural frequencies)
and achieved weight savings of as much as 15%

Hybrid Solid-lattice optimization

This is achieved in two stages. In the first stage, a concept level topology optimization is performed to partition solid, void and intermediate spaces and create lattice elements.

In the second stage the size (e.g., area of cross section at each end) is optimized for a final optimized structure.



Even after multiple attempts by varying the parameters controlling the topology optimization and/or eliminating some design constraints, the resulting design optimization failed to yield anticipated weight savings.

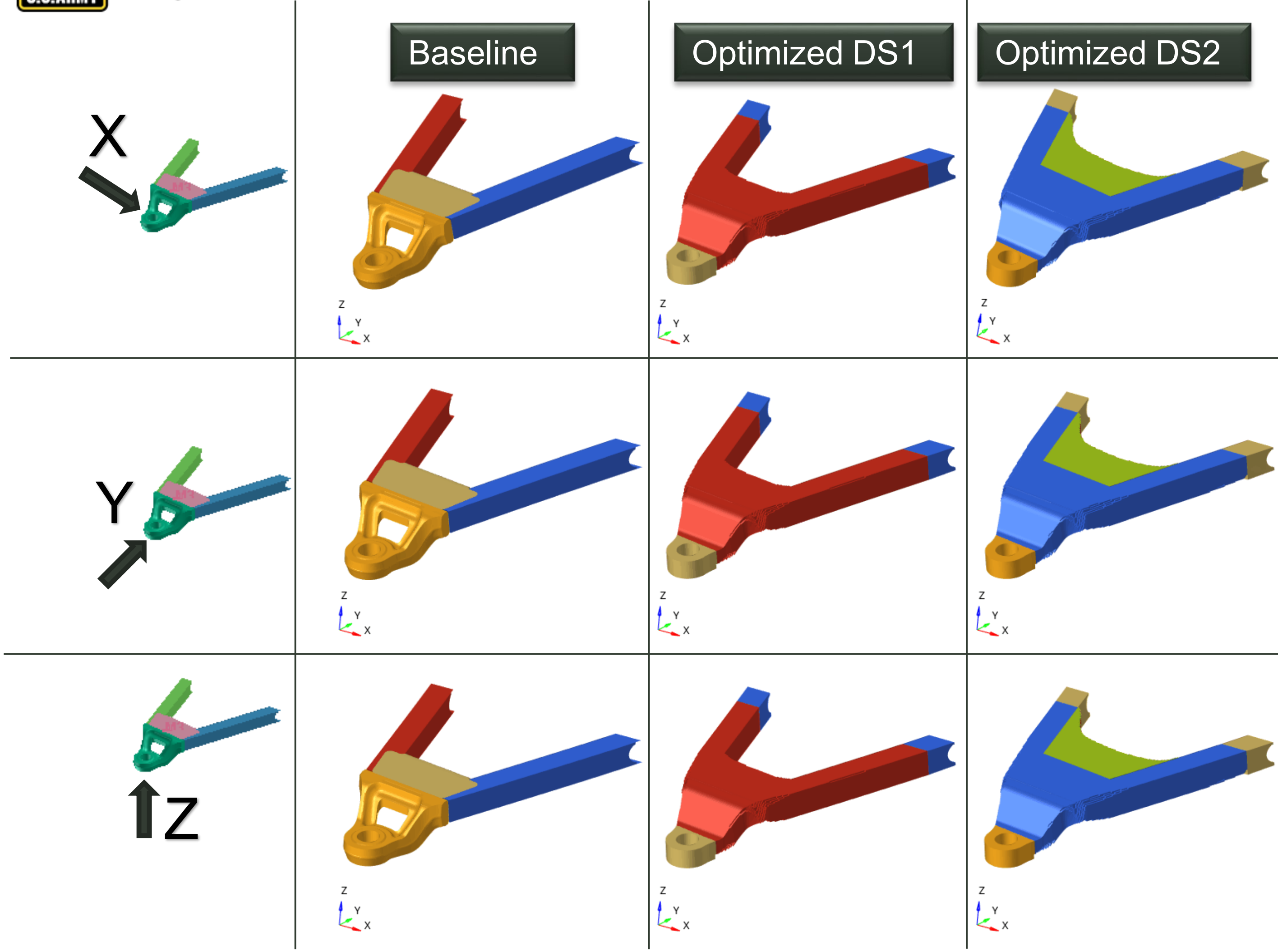
Results (Updated for FY19)

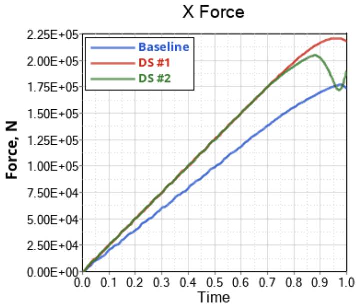
	Response Quantity			Baseline	DS #1	%Δ		DS #2	%Δ	
1	**Mass, kg**			**18.3**	**17.14**	**7%**	▲	**15.59**	**17%**	▲
2	Forces	Compliance, mm/kN	X	8.75E-03	7.97E-03	10%	▲	8.14E-03	7%	▲
3			Y	3.73E-02	3.46E-02	8%	▲	3.44E-02	8%	▲
4			Z	1.88E-01	1.64E-01	15%	▲	1.66E-01	13%	▲
5		Max Von Mises Stress, MPa	X	6.08	4.21	44%	▲	3.33	83%	▲
6			Y	8.26	6.20	33%	▲	7.97	4%	▲
7			Z	19.21	11.91	61%	▲	19.16	0%	▲
8	Moments	Compliance, rad/Nm	X	3.39E-06	2.95E-06	15%	▲	2.94E-06	15%	▲
9			Y	1.34E-06	1.19E-06	13%	▲	1.20E-06	12%	▲
10			Z	6.39E-07	5.53E-07	16%	▲	5.43E-07	18%	▲
11		Max Von Mises Stress, MPa	X	1.13E-01	8.23E-02	37%	▲	1.12E-01	1%	▲
12			Y	6.44E-02	5.09E-02	26%	▲	5.16E-02	25%	▲
13			Z	5.51E-02	4.50E-02	23%	▲	4.83E-02	14%	▲
		Mode Shape	Mode #							
14	Natural Frequencies, Hz	Vertical	#1	129	154	16%	▲	161	20%	▲
15		Lateral + twist	#2	506	570	11%	▲	666	24%	▲
16		Lateral + twist out of phase	#3	621	667	7%	▲	731	15%	▲
17	Maximum nonlinear buckling load, kN			21.7	22.1	-2%	▼	20.3	7%	▲
18	Fatigue damage (Notional load)			1000	16.4	5998%	▲	98	920%	▲

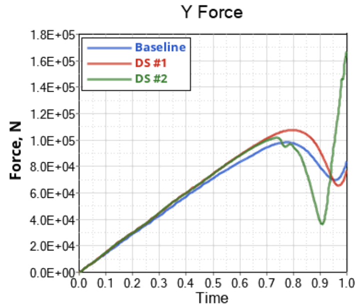
▲	Better. Lower compliance, lower stress, higher modal frequency
▼	Worse. Higher compliance, higher stress, lower modal frequency

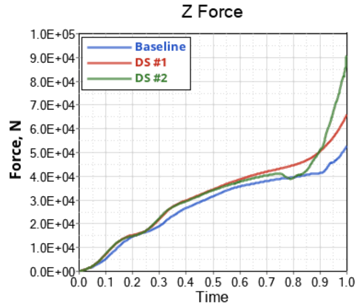
Both design spaces met/exceeded an average of
>12% for stiffness; >30% for strength ; >16% for natural frequencies)
and achieved weight savings of as much as 17%

Non linear buckling comparison #1



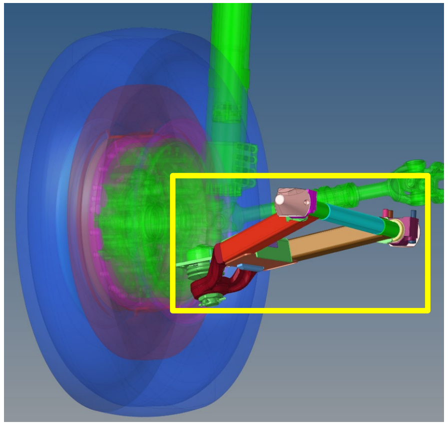


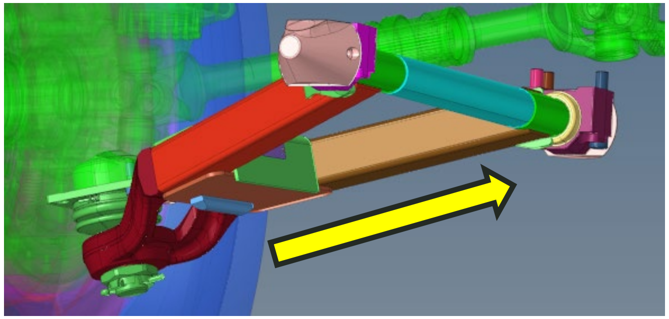




Both optimized design spaces show similar or better performance compared to baseline design.

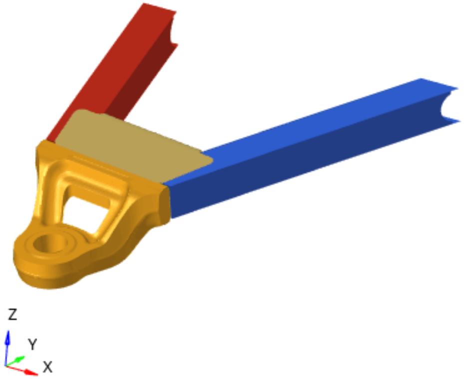
Non-linear buckling comparison #2



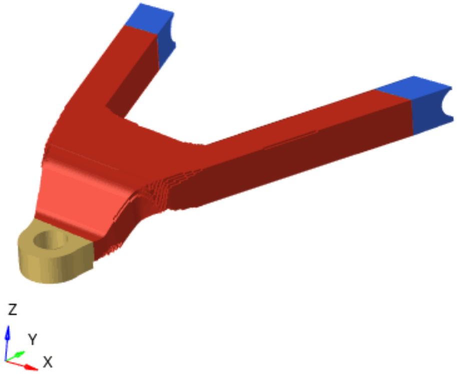


A follower force applied at the ball joint attachment to remain parallel to the longitudinal axis of the road arm

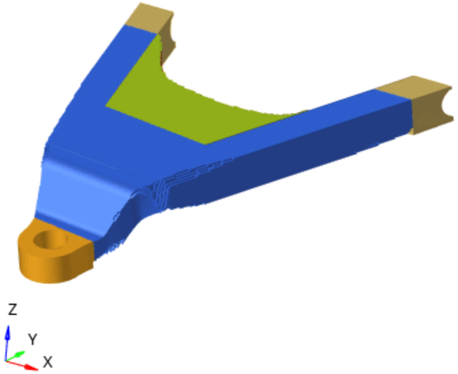
Baseline

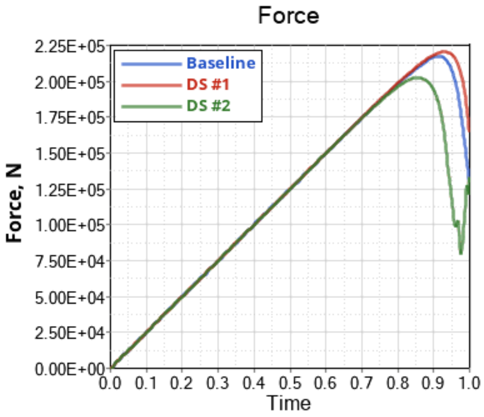


Optimized DS1



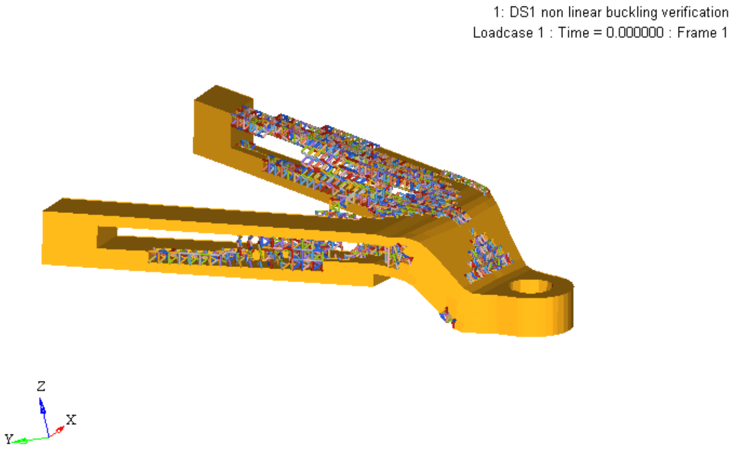
Optimized DS2

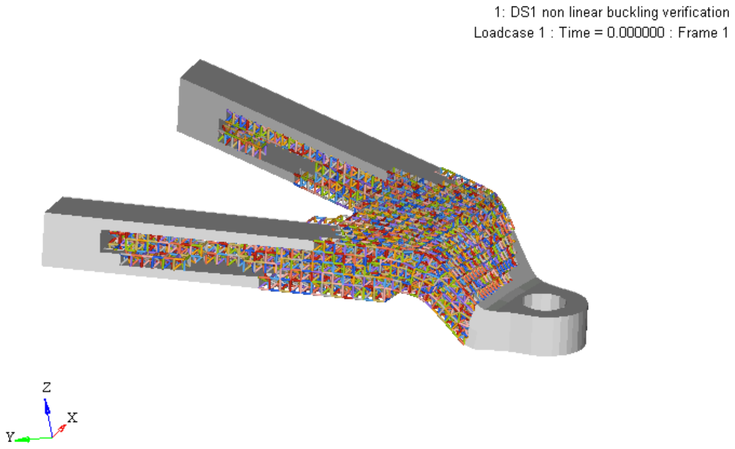


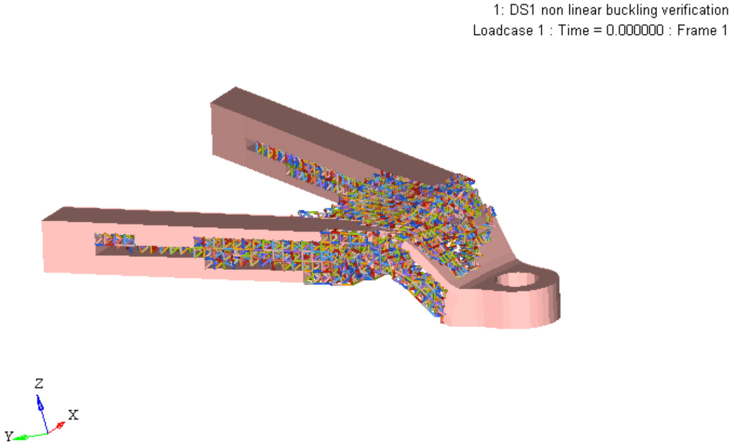


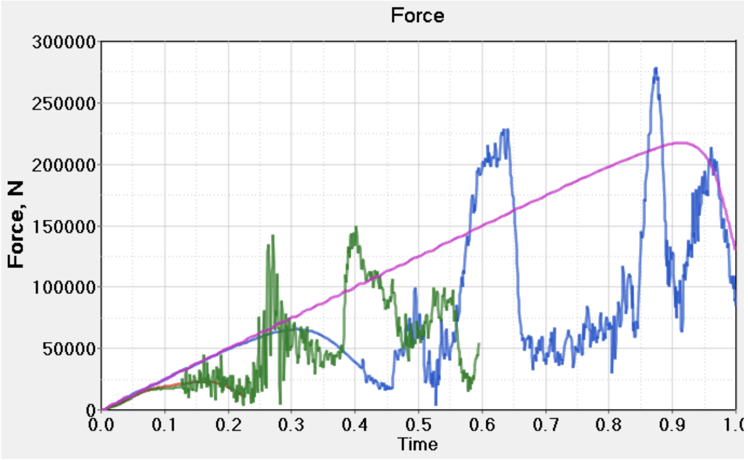
Optimized Design Space #2 did not meet the peak buckling load target (less by 8%) but can be engineered to meet the target by additional stiffening ribs. Optimized Design Space #1 exceeded the target by 1%

Non-linear buckling (Hybrid Solid-Lattice designs









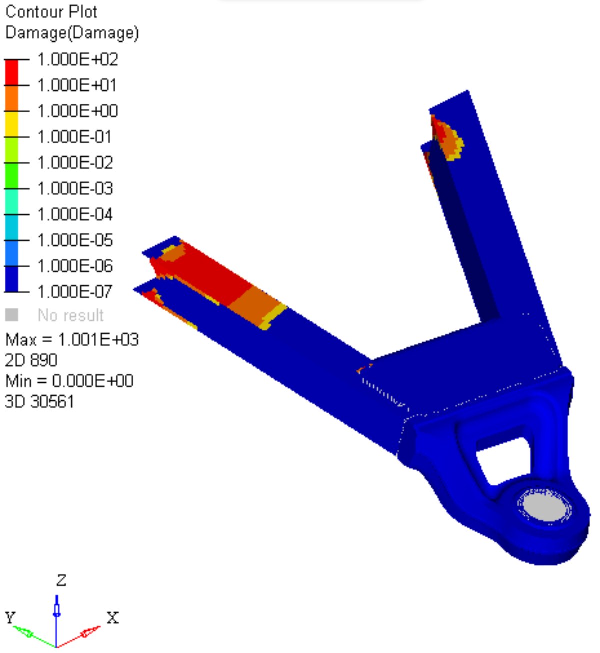
Many attempts to develop a hybrid solid-lattice structure resulted in solutions that failed to meet all the design constraints and did not meet the nonlinear buckling strength requirement.

Fatigue Life comparison

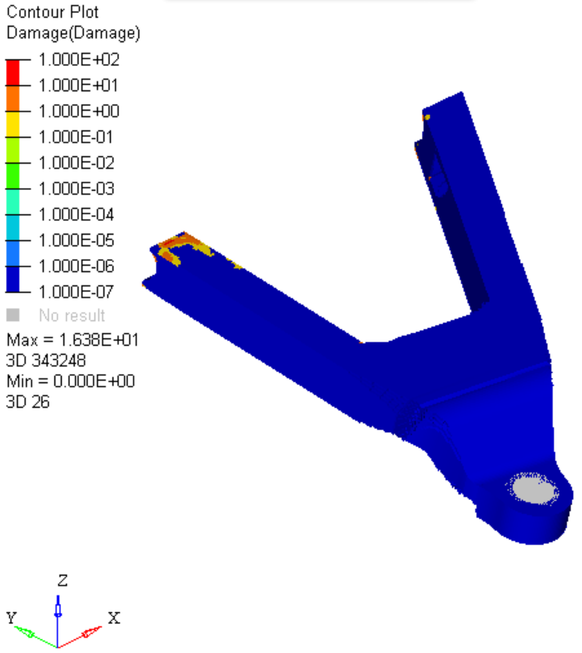
Multiaxial fatigue analysis performed on both optimized designs and compared against baseline design

- Multi axial loading using notional road load data (braking, cornering and pothole)
- Stress based damage model (Goodman)

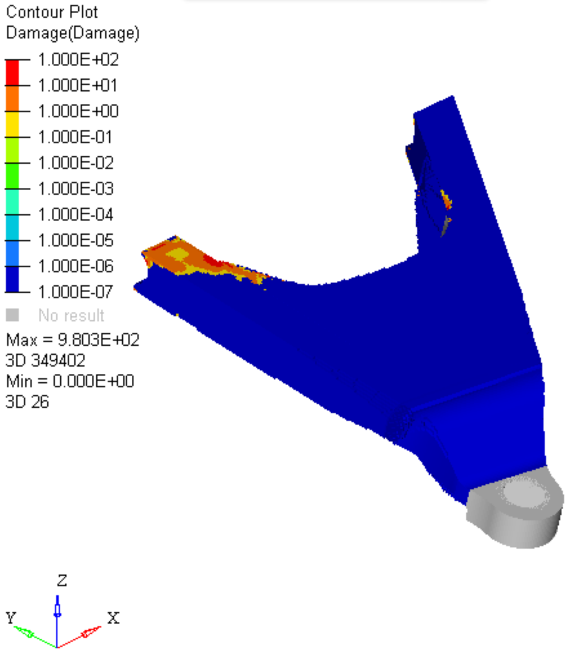
Baseline



Optimized DS1

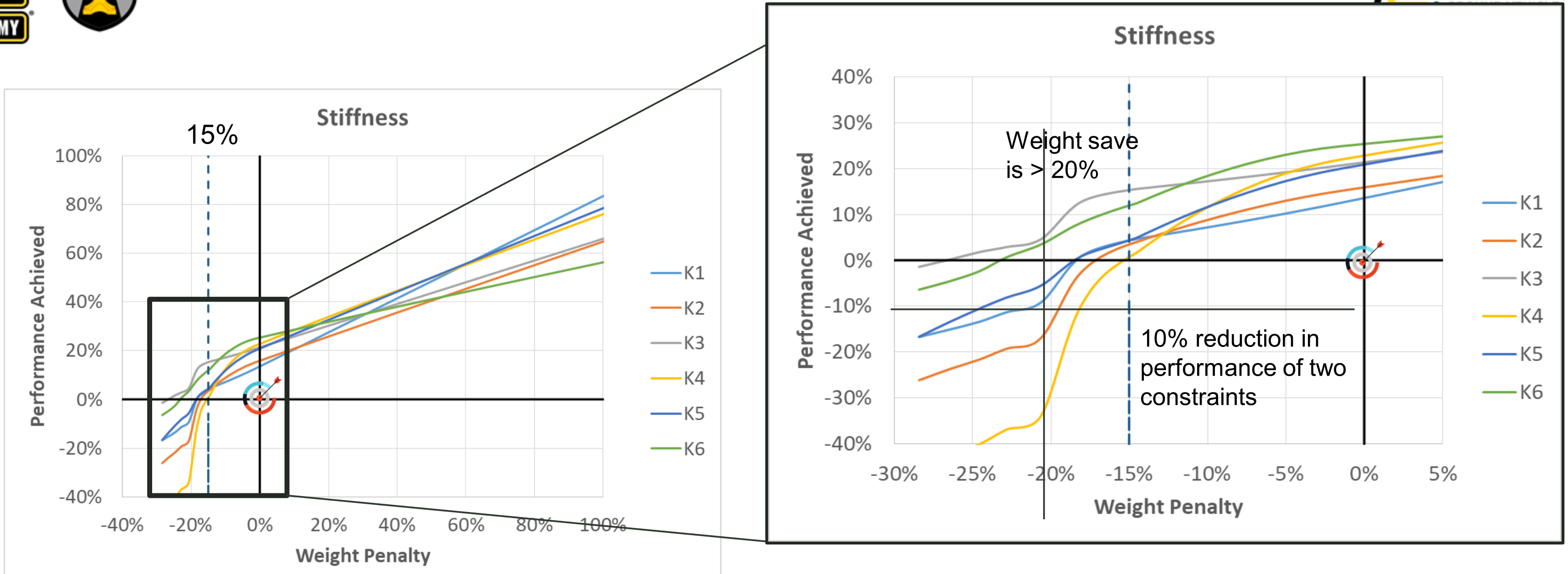


Optimized DS2



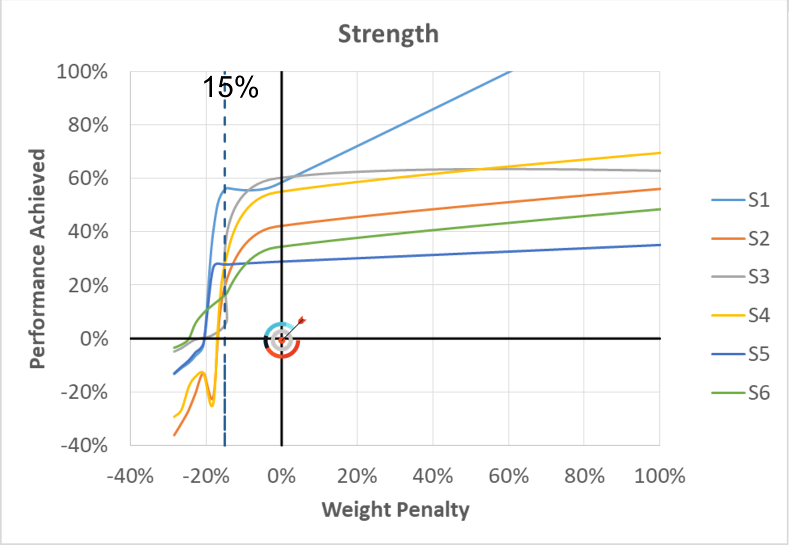
Both design spaces show remarkably less fatigue damage compared to the baseline design

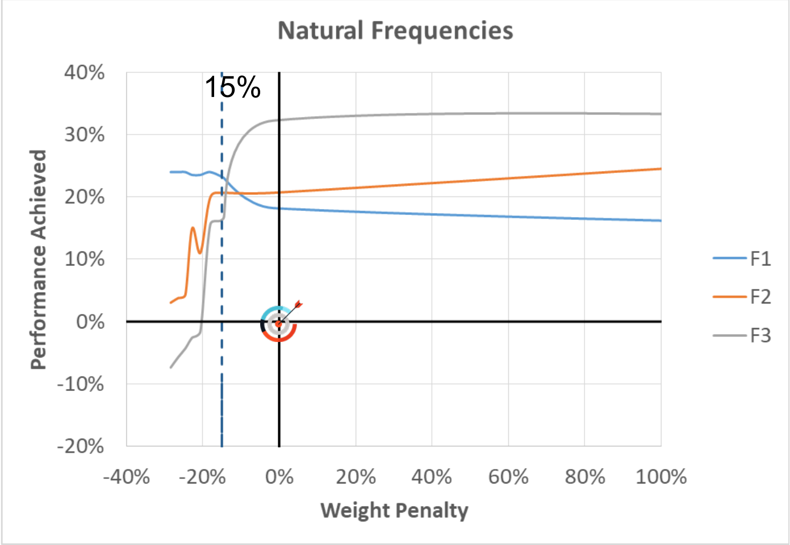
RESULTS: Design Space (#2) exploration



Weight save is > 20%

10% reduction in performance of two constraints





Further potential for weight save exists with more realistic (component design specific) constraints.

Conclusions & Future plans

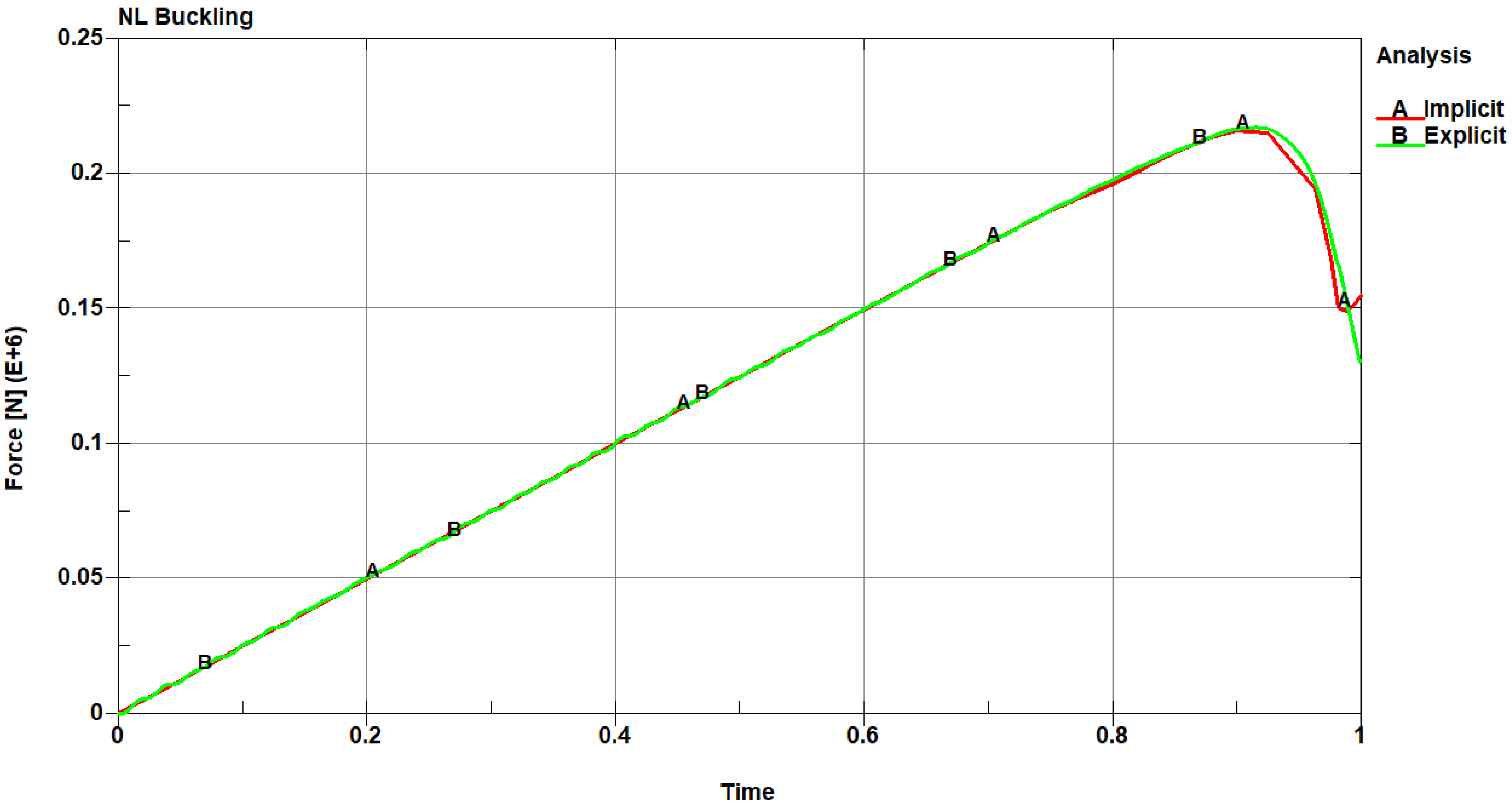
- Although constraints were established based on ideal welds the two design spaces explored performed ***equally or better*** in most of the performance metrics
- A 10% relaxation in performance constraints (very stringent to begin with) show a potential weight save of **> 20%**
- Hybrid solid-lattice design for this application was found to be not suitable as it failed to meet all the design constraints, including later added buckling strength requirement
- Nonlinear buckling and fatigue life were not part of the original design constraints but the optimized designs' performance are verified against baseline
    - Optimized Design Space #2 did not meet the peak buckling load target (less by 8%) but can be engineered to meet the target by additional stiffening ribs. Optimized Design Space #1 exceeded the target by 1%
    - Both design spaces showed significantly less fatigue damage when compared against the baseline design which results in increased life
- Design space #1 which occupies the current package space has a potential of weight save up to 7%, while Design space #2 which extends beyond the current package space (yet, available in vehicle) has a potential weight save of up to 17%

Planned for FY20

- Refine the baseline model to include actual welds, including fatigue and weld properties to establish more realistic performance targets
- Investigating including fatigue life in the design constraints
- Prepare the topology optimized version for verification with a prototype of a chosen optimized design through verification testing (using Road Dynamic loading)
- Validate this methodology on a different component/sub-system including more realistic performance objectives as design constraints

Back up slides

Comparison of Implicit vs Explicit Finite Element analysis



Material properties for 3d printing

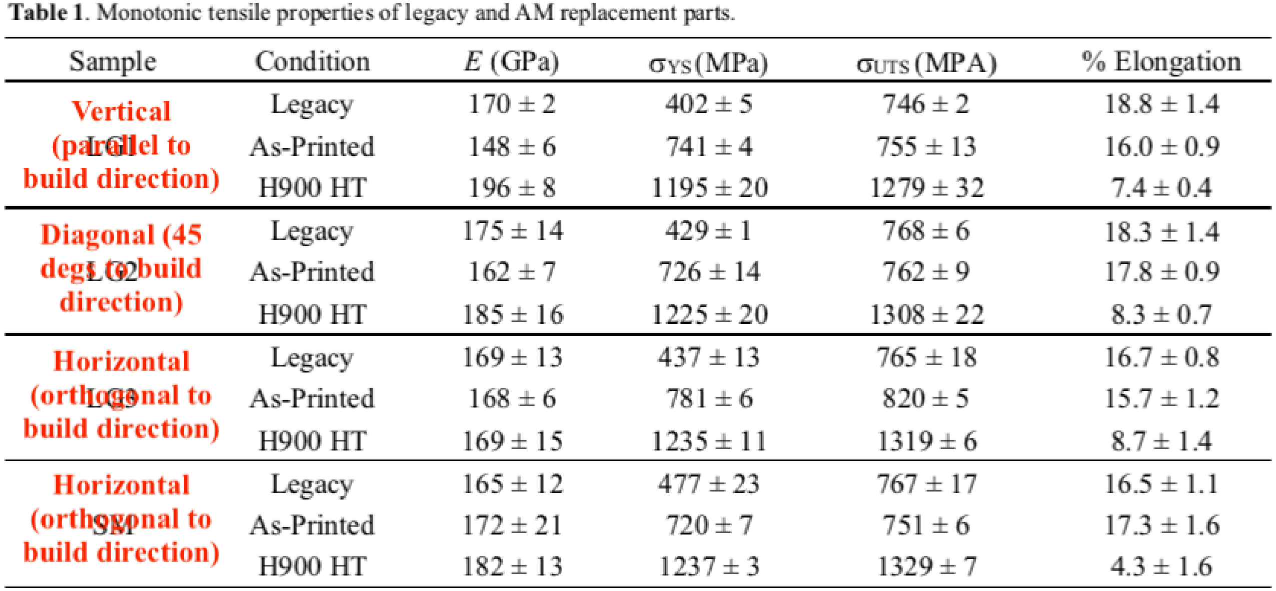
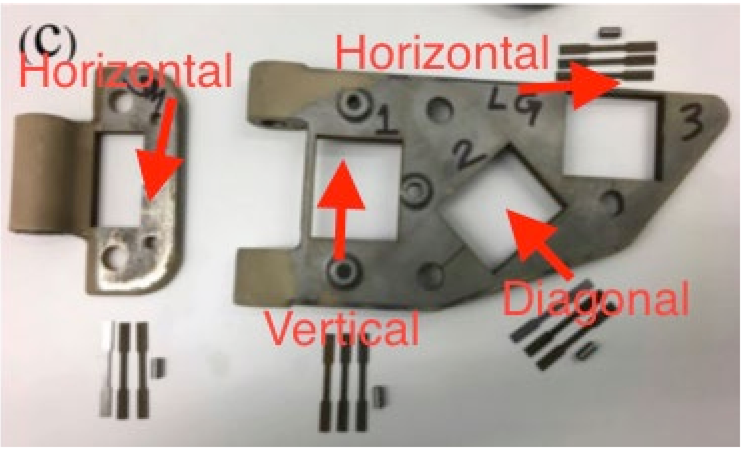


Table 1. Monotonic tensile properties of legacy and AM replacement parts.

Sample	Condition	*E* (GPa)	σ_{YS} (MPa)	σ_{UTS} (MPA)	% Elongation
Vertical (parallel to build direction) LG1	Legacy	170 ± 2	402 ± 5	746 ± 2	18.8 ± 1.4
	As-Printed	148 ± 6	741 ± 4	755 ± 13	16.0 ± 0.9
	H900 HT	196 ± 8	1195 ± 20	1279 ± 32	7.4 ± 0.4
Diagonal (45 degs to build direction) LG2	Legacy	175 ± 14	429 ± 1	768 ± 6	18.3 ± 1.4
	As-Printed	162 ± 7	726 ± 14	762 ± 9	17.8 ± 0.9
	H900 HT	185 ± 16	1225 ± 20	1308 ± 22	8.3 ± 0.7
Horizontal (orthogonal to build direction) LG3	Legacy	169 ± 13	437 ± 13	765 ± 18	16.7 ± 0.8
	As-Printed	168 ± 6	781 ± 6	820 ± 5	15.7 ± 1.2
	H900 HT	169 ± 15	1235 ± 11	1319 ± 6	8.7 ± 1.4
Horizontal (orthogonal to build direction) SM	Legacy	165 ± 12	477 ± 23	767 ± 17	16.5 ± 1.1
	As-Printed	172 ± 21	720 ± 7	751 ± 6	17.3 ± 1.6
	H900 HT	182 ± 13	1237 ± 3	1329 ± 7	4.3 ± 1.6



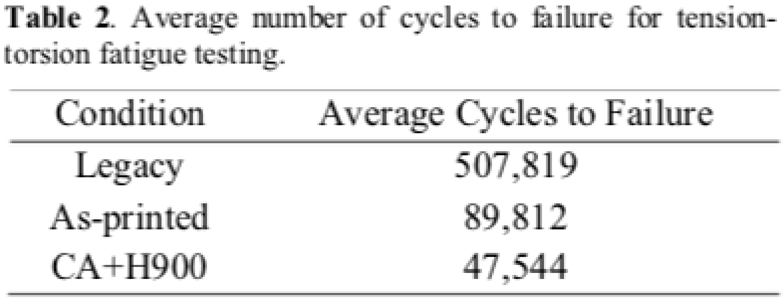
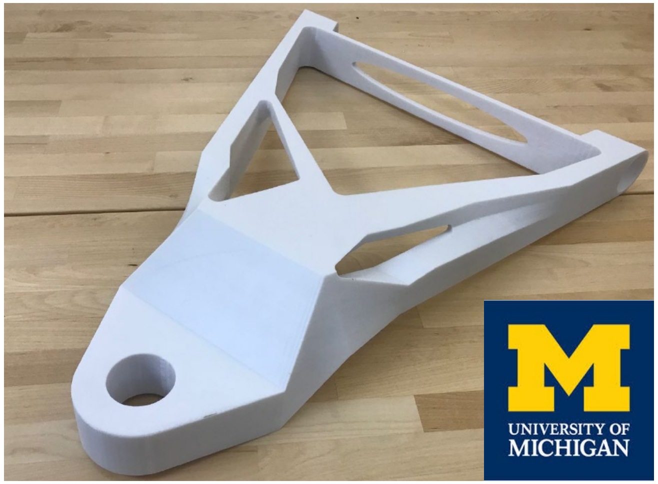


Table 2. Average number of cycles to failure for tension-torsion fatigue testing.

Condition	Average Cycles to Failure
Legacy	507,819
As-printed	89,812
CA+H900	47,544

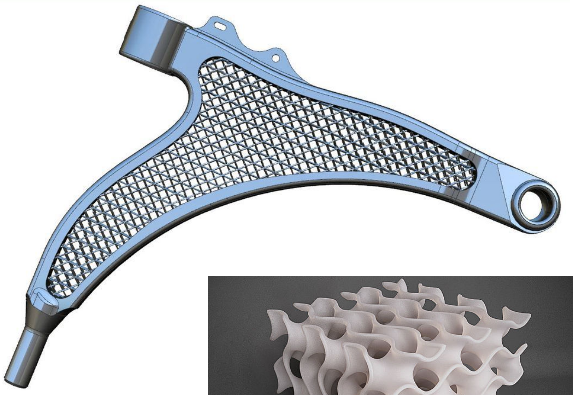
Conclusions / FUTURE WORK

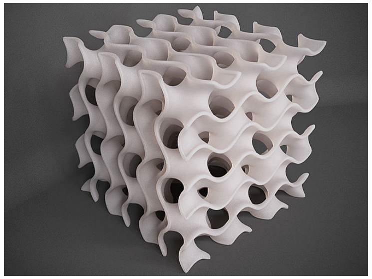
- A proof of concept modeling and simulation strategy has been demonstrated, identifying sizable weight save opportunities based on load-agonostic optimization methodology.
- The chosen design upon topology optimization yielded 15% weight, exceeded targets for stiffness (+10% avg) & strength (+32% avg) and first three natural frequencies (+16% avg)
  - In an independent study[5], a Senior Capstone project at University of Michigan, Ann Arbor, realized a 17.5% weight savings in the same component, but by employing known service loads.



Future research will focus on three main areas:

1. Constraint perturbation (relaxed by -10% → more stringent by +10%) to establish the Efficiency (∆weight / ∆perf) relationship between weight save and constraints.
2. Determine the feasibility of this approach to develop blended solid and lattice structures to exploit additional weight savings (such structures are highly 3D-printer friendly).
3. Validate this methodology on a different component/sub-system. Characterize identifiable characteristics of a part that enable weight savings with minimal loss of performance.





GYROID

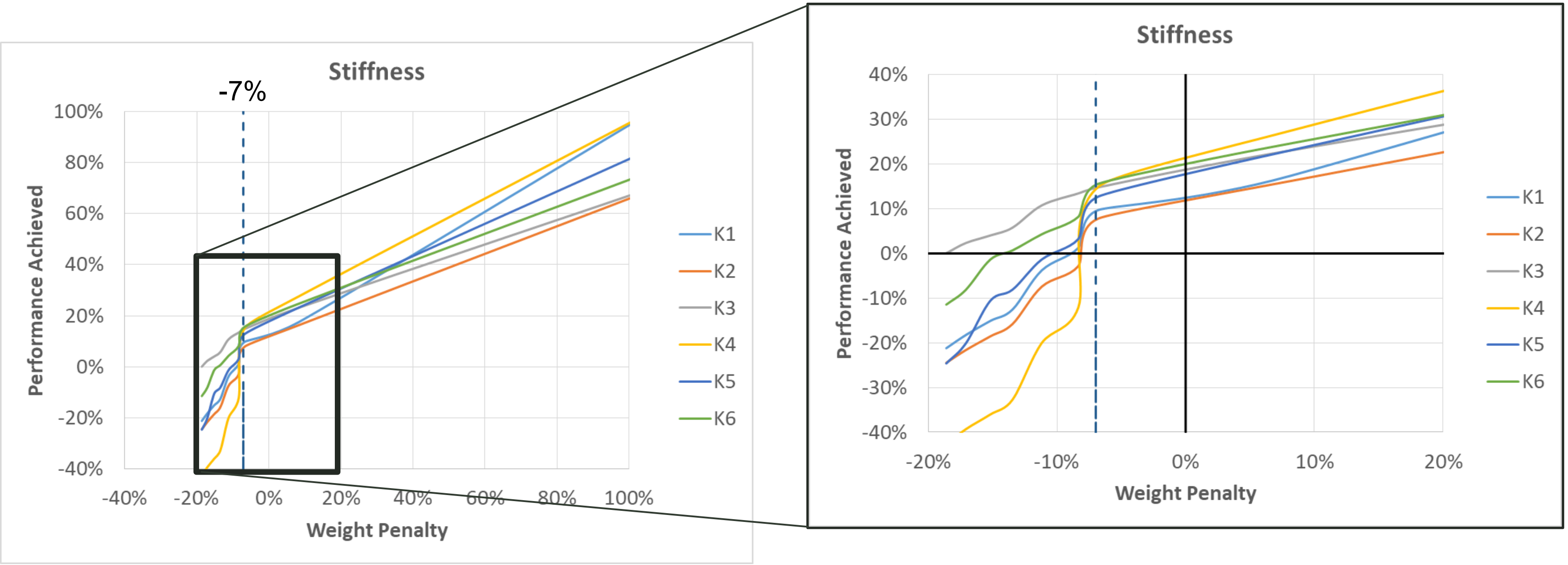
RESULTS: Design Space (#1) exploration

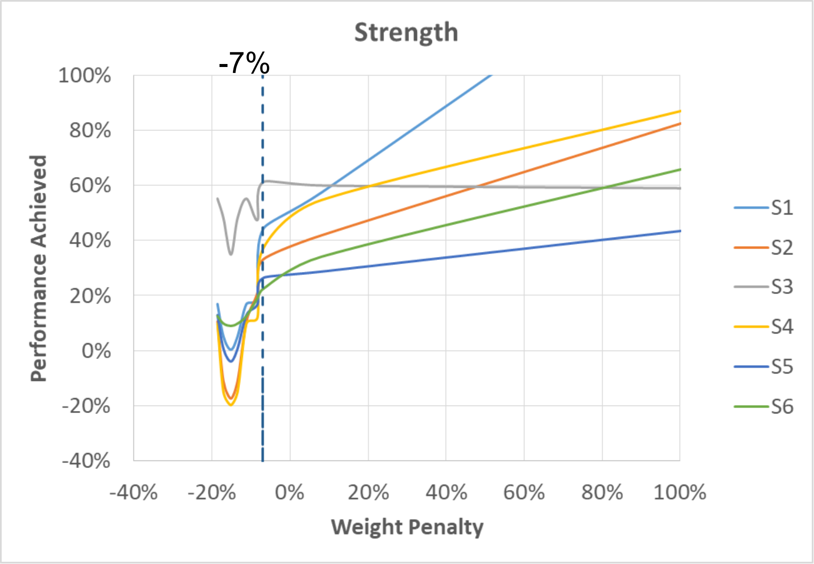
		Response Quantity		Baseline	Mat density > 90%	%Δ	> 80%	%Δ	> 70%	%Δ	> 60%	%Δ
1	**Mass, kg**			**18.3**	**15.43**	**19% ▲**	**15.63**	**17% ▲**	**15.89**	**15% ▲**	**16.13**	**13% ▲**
2	**Forces**	Compliance, mm/kN	X	8.75E-03	1.11E-02	-21% ▼	1.07E-02	-18% ▼	1.03E-02	-15% ▼	1.00E-02	-13% ▼
3			Y	3.73E-02	4.94E-02	-24% ▼	4.76E-02	-22% ▼	4.58E-02	-19% ▼	4.43E-02	-16% ▼
4			Z	1.88E-01	1.88E-01	0% ▲	1.84E-01	2% ▲	1.81E-01	4% ▲	1.78E-01	6% ▲
5		Max Von Mises Stress, MPa	X	6.08	5.20	17% ▲	5.78	5% ▲	6.06	0% ▲	5.78	5% ▲
6			Y	8.26	7.47	11% ▲	9.29	-11% ▼	10.00	-17% ▼	9.29	-11% ▼
7			Z	19.21	12.38	55% ▲	12.97	48% ▲	14.24	35% ▲	12.97	48% ▲
8	**Moments**	Compliance, rad/Nm	X	3.39E-06	5.92E-06	-43% ▼	5.59E-06	-39% ▼	5.30E-06	-36% ▼	5.04E-06	-33% ▼
9			Y	1.34E-06	1.78E-06	-25% ▼	1.68E-06	-20% ▼	1.50E-06	-11% ▼	1.46E-06	-8% ▼
10			Z	6.39E-07	7.22E-07	-11% ▼	6.96E-07	-8% ▼	6.48E-07	-1% ▼	6.35E-07	1% ▲
11		Max Von Mises Stress, MPa	X	1.13E-01	1.03E-01	10% ▲	1.33E-01	-15% ▼	1.41E-01	-20% ▼	1.33E-01	-15% ▼
12			Y	6.44E-02	5.70E-02	13% ▲	6.39E-02	1% ▲	6.70E-02	-4% ▼	6.39E-02	1% ▲
13			Z	5.51E-02	4.90E-02	13% ▲	5.02E-02	10% ▲	5.06E-02	9% ▲	5.02E-02	10% ▲
	Natural Frequencies, Hz	Mode Shape	Mode #									
14		Vertical	#1	129	166	22% ▲	167	23% ▲	166	22% ▲	166	22% ▲
15		Lateral + twist	#2	506	550	8% ▲	566	11% ▲	576	12% ▲	583	13% ▲
16		Lateral + twist out of phase	#3	621	604	-3% ▼	607	-2% ▼	611	-2% ▼	612	-1% ▼
17		Vertical 2nd order	#4	761	722	-5% ▼	727	-5% ▼	732	-4% ▼	732	-4% ▼
18		Lateral higher order	#5	1218	1126	-8% ▼	1062	-15% ▼	1044	-17% ▼	1058	-15% ▼
19		Complex	#6	1469	1421	-3% ▼	1491	1% ▲	1342	-9% ▼	1354	-8% ▼

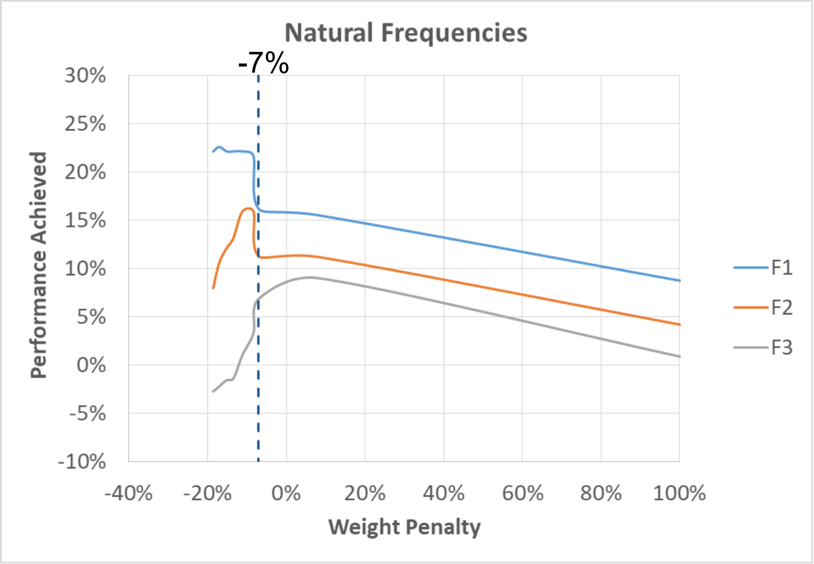
Results: Design Space (#1) exploration (Continued)

Response Quantity				Baseline	> 50%	%Δ	> 40%		> 25% (FINAL)	%Δ	> 10%	%Δ	> 0%	%Δ
1	**Mass, kg**			**18.3**	**16.46**	**11% ▲**	**16.89**	**8% ▲**	**17.14**	**7% ▲**	**19.93**	**-8% ▼**	**37.59**	**-105% ▼**
2	**Forces**	Compliance, mm/kN	X	8.75E-03	9.09E-03	-4% ▼	8.64E-03	1% ▲	7.97E-03	10% ▲	7.45E-03	17% ▲	4.39E-03	50% ▲
3			Y	3.73E-02	4.03E-02	-7% ▼	3.84E-02	-3% ▼	3.46E-02	8% ▲	3.21E-02	16% ▲	2.21E-02	41% ▲
4			Z	1.88E-01	1.70E-01	11% ▲	1.66E-01	13% ▲	1.64E-01	15% ▲	1.53E-01	23% ▲	1.11E-01	41% ▲
5		Max Von Mises Stress, MPa	X	6.08	5.20	17% ▲	5.12	19% ▲	4.21	44% ▲	3.86	58% ▲	2.40	61% ▲
6			Y	8.26	7.47	11% ▲	6.82	21% ▲	6.20	33% ▲	5.82	42% ▲	4.47	46% ▲
7			Z	19.21	12.38	55% ▲	13.03	47% ▲	11.91	61% ▲	12.01	60% ▲	12.09	37% ▲
8	**Moments**	Compliance, rad/Nm	X	3.39E-06	4.24E-06	-20% ▼	3.86E-06	-12% ▼	2.95E-06	15% ▲	2.66E-06	27% ▲	1.70E-06	50% ▲
9			Y	1.34E-06	1.36E-06	-1% ▼	1.30E-06	3% ▲	1.19E-06	13% ▲	1.09E-06	23% ▲	7.26E-07	46% ▲
10			Z	6.39E-07	6.13E-07	4% ▲	5.91E-07	8% ▲	5.53E-07	16% ▲	5.13E-07	25% ▲	3.63E-07	43% ▲
11		Max Von Mises Stress, MPa	X	1.13E-01	1.03E-01	10% ▲	1.01E-01	12% ▲	8.23E-02	37% ▲	7.31E-02	55% ▲	5.99E-02	47% ▲
12			Y	6.44E-02	5.70E-02	13% ▲	5.51E-02	17% ▲	5.09E-02	26% ▲	5.00E-02	29% ▲	4.46E-02	31% ▲
13			Z	5.51E-02	4.90E-02	13% ▲	4.63E-02	19% ▲	4.50E-02	23% ▲	4.11E-02	34% ▲	3.29E-02	40% ▲
	Natural Frequencies, Hz	Mode Shape	Mode #											
14		Vertical	#1	129	166	22% ▲	165	22% ▲	154	16% ▲	153	16% ▲	141	8% ▲
15		Lateral + twist	#2	506	602	16% ▲	602	16% ▲	570	11% ▲	570	11% ▲	526	4% ▲
16		Lateral + twist out of phase	#3	621	627	1% ▲	642	3% ▲	667	7% ▲	682	9% ▲	623	0% ▲
17		Vertical 2nd order	#4	761	757	-1% ▼	766	1% ▲	807	6% ▲	826	8% ▲	616	-24% ▼
18		Lateral higher order	#5	1218	1383	12% ▲	1156	-5% ▼	1254	3% ▲	1310	7% ▲	1489	18% ▲
19		Complex	#6	1469	1664	12% ▲	1395	-5% ▼	1422	-3% ▼	1495	2% ▲	1716	14% ▲

RESULTS: Design Space (#1) exploration







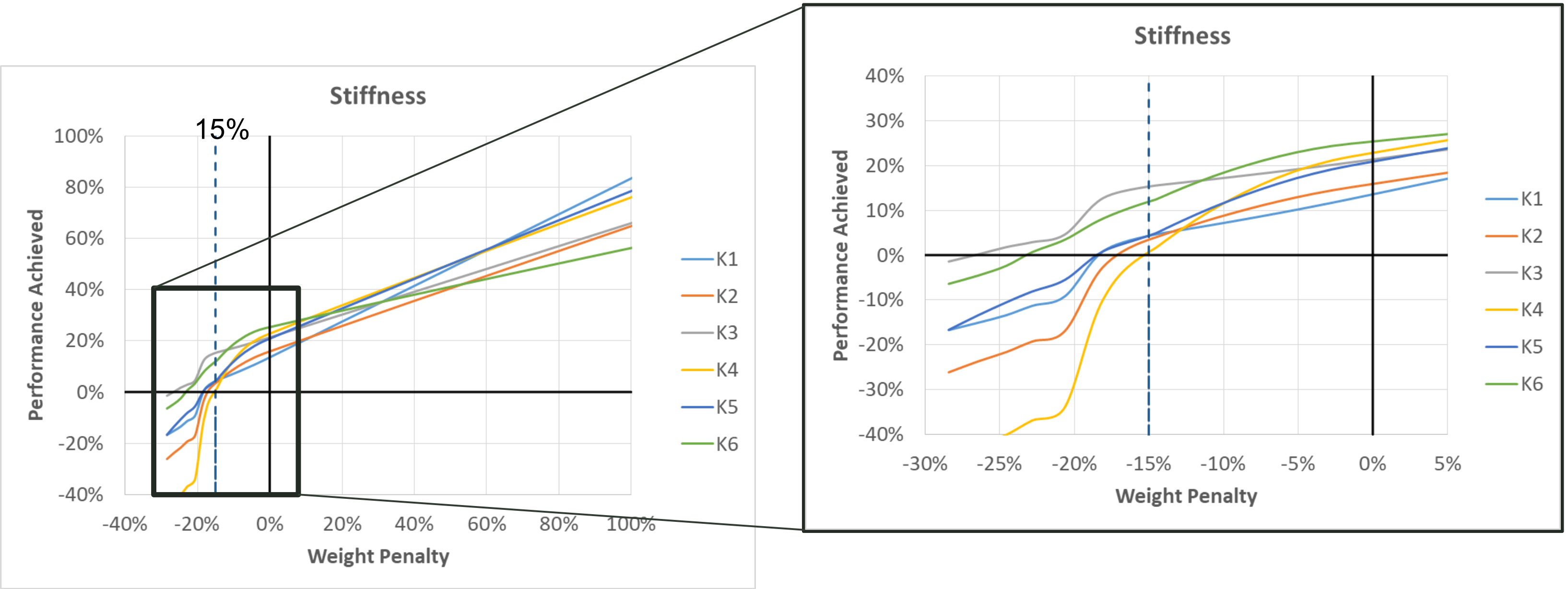
RESULTS: Design Space (#2) exploration

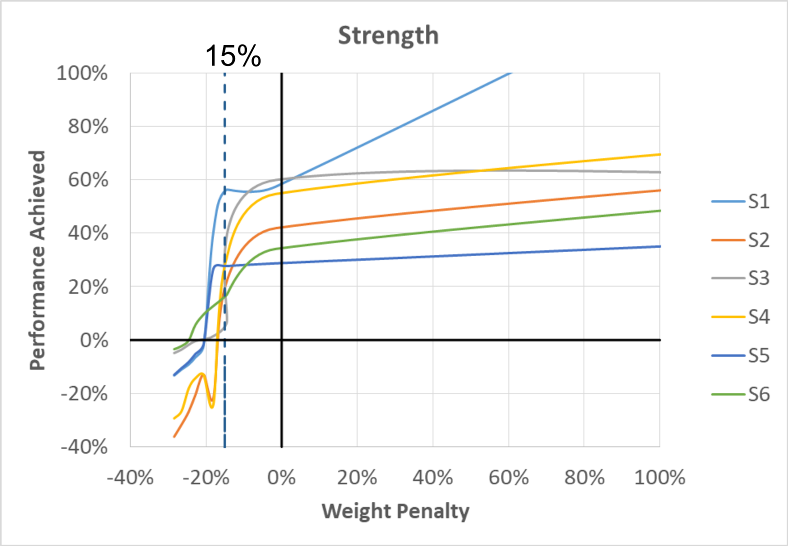
		Response Quantity		Baseline	Mat density > 90%	%Δ	> 80%	%Δ	> 70%	%Δ	> 60%	%Δ
1		**Mass, kg**		**18.3**	**14.25**	**28% ▲**	**14.47**	**26% ▲**	**14.69**	**25% ▲**	**14.9**	**23% ▲**
2	**Forces**	Compliance, mm/kN	X	8.75E-03	1.05E-02	-17% ▼	1.03E-02	-15% ▼	1.01E-02	-13% ▼	9.86E-03	-11% ▼
3			Y	3.73E-02	5.05E-02	-26% ▼	4.89E-02	-24% ▼	4.76E-02	-22% ▼	4.62E-02	-19% ▼
4			Z	1.88E-01	1.91E-01	-1% ▼	1.88E-01	0% ▲	1.85E-01	2% ▲	1.83E-01	3% ▲
5		Max Von Mises Stress, MPa	X	6.08	7.01	-13% ▼	6.83	-11% ▼	6.69	-9% ▼	6.50	-6% ▼
6			Y	8.26	12.94	-36% ▼	12.08	-32% ▼	11.28	-27% ▼	10.40	-21% ▼
7			Z	19.21	20.19	-5% ▼	19.92	-4% ▼	19.55	-2% ▼	19.28	-0% ▼
8	**Moments**	Compliance, rad/Nm	X	3.39E-06	6.13E-06	-45% ▼	5.89E-06	-42% ▼	5.66E-06	-40% ▼	5.37E-06	-37% ▼
9			Y	1.34E-06	1.61E-06	-17% ▼	1.55E-06	-13% ▼	1.50E-06	-11% ▼	1.46E-06	-8% ▼
10			Z	6.39E-07	6.83E-07	-6% ▼	6.70E-07	-5% ▼	6.55E-07	-2% ▼	6.35E-07	1% ▲
11		Max Von Mises Stress, MPa	X	1.13E-01	1.60E-01	-29% ▼	1.54E-01	-27% ▼	1.38E-01	-18% ▼	1.32E-01	-14% ▼
12			Y	6.44E-02	7.40E-02	-13% ▼	7.19E-02	-10% ▼	7.01E-02	-8% ▼	6.79E-02	-5% ▼
13			Z	5.51E-02	5.71E-02	-3% ▼	5.64E-02	-2% ▼	5.52E-02	-0% ▼	5.22E-02	6% ▲
	Natural Frequencies, Hz	Mode Shape	Mode #									
14		Vertical	#1	129	170	24% ▲	170	24% ▲	170	24% ▲	169	24% ▲
15		Lateral + twist	#2	506	522	3% ▲	526	4% ▲	529	4% ▲	595	15% ▲
16		Lateral + twist out of phase	#3	621	578	-7% ▼	587	-6% ▼	595	-4% ▼	605	-3% ▼
17		Vertical 2nd order	#4	761	660	-15% ▼	657	-16% ▼	670	-14% ▼	674	-13% ▼
18		Lateral higher order	#5	1218	737	-65% ▼	740	-65% ▼	743	-64% ▼	746	-63% ▼
19		Complex	#6	1469	1158	-27% ▼	1168	-26% ▼	1176	-25% ▼	1183	-24% ▼

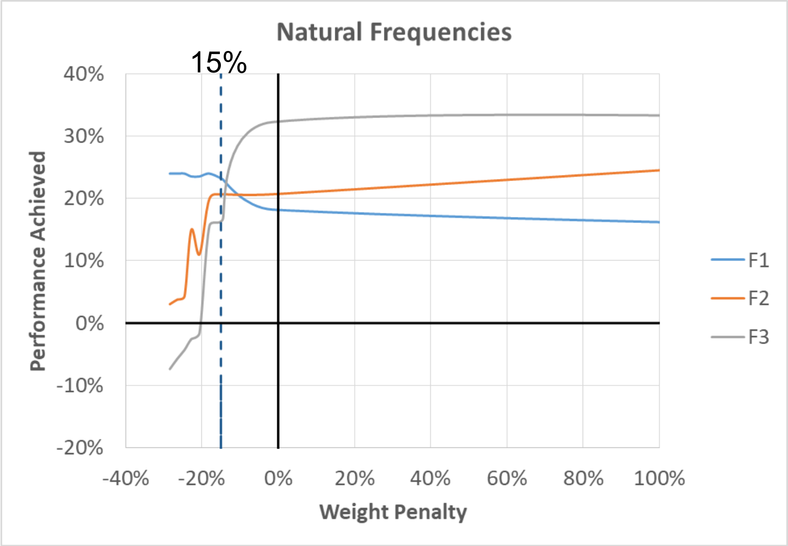
RESULTS: Design Space (#2) exploration (Continued)

		Response Quantity		Baseline	> 50%	%Δ	> 40%		> 25% (FINAL)	%Δ	> 10%	%Δ	> 0%	%Δ
1		**Mass, kg**		**18.3**	**15.17**	**21%▲**	**15.5**	**18%▲**	**15.97**	**15%▲**	**18.04**	**1%▲**	**65.89**	**-260%▼**
2	**Forces**	Compliance, mm/kN	X	8.75E-03	9.63E-03	-9% ▼	8.67E-03	1% ▲	8.36E-03	5% ▲	7.77E-03	13%▲	2.96E-03	195% ▲
3			Y	3.73E-02	4.49E-02	-17%▼	3.83E-02	-3% ▼	3.59E-02	4% ▲	3.24E-02	15%▲	1.54E-02	142% ▲
4			Z	1.88E-01	1.80E-01	5% ▲	1.67E-01	13% ▲	1.63E-01	16% ▲	1.56E-01	21%▲	7.93E-02	137% ▲
5		Max Von Mises Stress, MPa	X	6.08	6.21	-2% ▼	4.33	40% ▲	3.89	56% ▲	3.86	58%▲	1.79	240% ▲
6			Y	8.26	9.49	-13%▼	10.55	-22%▼	6.79	22% ▲	5.82	42%▲	4.72	75% ▲
7			Z	19.21	19.15	0% ▲	18.93	1% ▲	18.08	6% ▲	12.01	60%▲	12.16	58% ▲
8	**Moments**	Compliance, rad/Nm	X	3.39E-06	5.13E-06	-34%▼	3.76E-06	-10%▼	3.34E-06	2% ▲	2.78E-06	22%▲	1.31E-06	159% ▲
9			Y	1.34E-06	1.42E-06	-6% ▼	1.33E-06	1% ▲	1.28E-06	5% ▲	1.12E-06	20%▲	4.98E-07	169% ▲
10			Z	6.39E-07	6.18E-07	3% ▲	5.91E-07	8% ▲	5.69E-07	12% ▲	5.12E-07	25%▲	3.13E-07	104% ▲
11		Max Von Mises Stress, MPa	X	1.13E-01	1.30E-01	-13%▼	1.49E-01	-24%▼	8.67E-02	30% ▲	7.31E-02	55%▲	5.99E-02	89% ▲
12			Y	6.44E-02	6.53E-02	-1% ▼	5.08E-02	27% ▲	5.04E-02	28% ▲	5.00E-02	29%▲	4.44E-02	45% ▲
13			Z	5.51E-02	5.03E-02	10% ▲	4.89E-02	13% ▲	4.72E-02	17% ▲	4.11E-02	34%▲	3.28E-02	68% ▲
	Natural Frequencies, Hz	Mode Shape	Mode #											
14		Vertical	#1	129	169	24% ▲	170	24% ▲	168	23% ▲	158	18%▲	150	14% ▲
15		Lateral + twist	#2	506	569	11% ▲	632	20% ▲	638	21% ▲	638	21%▲	730	31% ▲
16		Lateral + twist out of phase	#3	621	611	-2% ▼	735	16% ▲	744	17% ▲	916	32%▲	916	32% ▲
17		Vertical 2nd order	#4	761	677	-12%▼	790	4% ▲	802	5% ▲	1070	29%▲	1070	29% ▲
18		Lateral higher order	#5	1218	1061	-15%▼	1069	-14%▼	1352	10% ▲	1348	10%▲	1348	10% ▲
19		Complex	#6	1469	1190	-23%▼	1194	-23%▼	1554	5% ▲	1535	4% ▲	1535	4% ▲

Results: Design Space (#2) exploration







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References

1. Kulkarni, K. and Thyagarajan, R., "Optimizing the Effects of Body Attachment Stiffness on Steering Column In-Vehicle Modes," SAE Technical Paper 2001-01-0041, 2001, doi:10.4271/2001-01-0041
2. Ravi Thyagarajan, Alex Akkerman, Mike Burger, Nielen Stander, Bob Kuhn, & Hrabri Rajic (2000). “Shape Optimization of Instrument Panel Components For Crashworthiness Using Distributed Computing”. Paper no. 2000-01-2682, IBEC-2000, SAE, Detroit, MI
3. C-J Chen, Mohammed Usman, David Bauer & Ravi Thyagarajan (1998). “Reduction of Instrument Panel Manufacturing Cost by Using Design Optimization”. Paper no. 982370, IBEC-98 International Body Engineering Conference, SAE
4. Dwayne Day, Rapporteur (2018). “Globalization of Defense Materials and Manufacturing: Proceedings of a Workshop”, National Materials and Manufacturing Board, Division on Engineering and Physical Sciences, National Academy of Sciences, National Academies Press
5. Breanna DeCocker, Michael Fisher, Kaitlyn Haller, Drake Kress & Magel Su (2018). “Optimized Structural Components For Land Vehicles Produced By Additive Manufacturing”. Senior Capstone Project (ENG 490), University of Michigan, Ann Arbor
6. Andrea Rindi, Enrico Meli, Enrico Boccini, Guiseppe Lurisi, Simone Corbo and Stefano Falomi (2016), Journal of Engineering for Gas turbines and power
7. T. E. Burns (2005) “A reevaluation of the SIMP method with filtering and an alternative formulation for solid-void topology optimization”, Structural Multidisciplinary Optimization 30: 428–436.
8. G.I.N. Rozvany (2001) “Aims, Scope, methods, history and unified terminology of computer-aided topology optimization in structural mechanics”, Structural Multidisciplinary Optimization 21: 90–108

Qualifications

Dr. Ravi Thyagarajan received his B.Tech. degree in Mechanical Engineering from the Indian Institute of Technology-Madras, India, and his M.S. and Ph.D. degrees in Applied Mechanics from the California Institute of Technology, Pasadena. He has three patents and has written over 80 technical papers and is Co-organizer of SAE Congress sessions as well as a Journal Editor for the SAE Journals. He is a past recipient of the Forest R McFarland Award from SAE for outstanding contributions to SAE. He received the 2010 and 2012 Army Materiel Command Systems Analysis awards. In 2013 and 2015, he was coauthor for the Best Paper Awards at the GVSETS Symposium. He was accepted in 2012 to the TARDEC Research Reviewer Board as a Senior Technical Specialist, served a three-year developmental assignment as the TARDEC Deputy Chief Scientist and currently is the Senior Technical Expert (STE) in Materials/Product Lifecycle Engineering.

In 2017, Dr. Thyagarajan was presented the Department of the Army Commander’s Award for Civilian Service and in 2018, Dr. Thyagarajan was elected as a Fellow of the Society of Automotive Engineers (SAE).

Mr. Kumar B Kulkarni received his Bachelor of Engineering degree in Mechanical engineering from Bangalore University, India, and M.S. degree in Mechanical Engineering from the University of Toledo, Ohio. He has a wide ranging automotive product development experience (>20 years) using Computer Aided Engineering tools while working at Ford Motor Company and Visteon Corporation as a Technical Specialist in Automotive Interiors Engineering. He has three patents and has several technical papers published at SAE conferences. He has been working in the Analytics group within TARDEC since 2011, performing underbody blast simulation analysis and developing/evaluating countermeasures and mitigation technologies to improve soldier protection and survivability. His current areas of interests include structural optimization, mobility and autonomy of ground system vehicles.

Technical publications of PI(s)

1. Gallmeyer, T., Dahal, J., Stebner, A., Thyagarajan, R., Santiago, J.M., Pilchak, A., Nuechterlein, J. (2018) "Systematic Development Of Framework For Validation And Performance Quantification Of Additively Manufactured (AM) Replacement Parts For Structural Steel Applications", *Army Science & Technology Symposium and Showcase, Washington, D.C., Aug 2018. DTIC Report # AD1059839*
2. Zhang, G., Thyagarajan, R., Kulkarni, K., Vlahopoulos, N. (2018) "Elements Of Set-based Design For Effective Decision Making In Army Vehicle Applications", *Army Science & Technology Symposium and Showcase, Washington, D.C., Aug 2018. DTIC Report # AD1059842*
3. Bennett, A., Vlahopoulos, N., Jiang, W., Castanier, M., Thyagarajan, R., Shurin S. (2018) "Modeling of Shear Thickening Fluids for Analysis of Energy Absorption Under Impulse Loading", *2018 NDIA Ground Vehicle Systems Engineering and Technology Symposium, Novi, Michigan, Aug 2018*
4. Ramalingam, J. and Thyagarajan, R., (2018) "A Fast Running Loading Methodology for Ground Vehicle Underbody Blast Events," *SAE Technical Paper 2018-01-0620, 2018, https://doi.org/10.4271/2018-01-0620*
5. Thyagarajan, R., and Ramalingam, J., (2017) "Analysis of Design Range for a Stroking Seat on a Stroking Floor to Mitigate Blast Loading Effects," *NATO Science and Technology Office (STO) Specialist Meeting AVT-265 /RSM-044 on "Integrated Virtual NATO Vehicle Development*
6. Babu, V., Thyagarajan, R., and Ramalingam, J., (2017) "Faster Method of Simulating Military Vehicles Exposed to Fragmenting Underbody IED Threats," *SAE Technical Paper 2017-01-0264, 2017, doi:10.4271/2017-01-0264. SAE World Congress, Detroit, MI*
7. Babu, V., Kulkarni, K., Kankanalapalli, S., Thyagarajan, R. (2016). "Sensitivity of Particle Size in Discrete Element Method to Particle Gas Method (DEM_PGM) Coupling in Underbody Blast Simulations" *14th International LS-DYNA Users Conference, Dearborn, Michigan. DTIC Report # AD A1011313.*
8. Jiang, W., A. Bennett, N. Vlahopoulos, M. Castanier, R. Thyagarajan. (2016). "A Reduced-Order Model for Evaluating the Dynamic Response of Multilayer Plates to Impulsive Loads." *SAE Int. J. Passenger Cars-Mechanical Systems, 2016-01-0307, Vol. 9, No. 1, pp 83-89*.
9. Jiang, Weiran, Vlahopoulos, Nickolas, Castanier, Matthew P, Thyagarajan, Ravi, Mohammad, Syed. (2015) "Tuning material and component properties to reduce weight and increase blastworthiness of a notional V-hull structure", *Case Studies in Mechanical Systems and Signal Processing (Elsevier), Vol. 2, pp 19-28*
10. Sivasuthan, S., Karthik, V., Mathialakan, T., Rawashdeh, M., Jayakumar, P., Thyagarajan, R., Hoole, S (2015) "GPU computations for finite element optimization: A review and some issues to be addressed". *Revue Roumaine Des Sciences Techniques, Vol. 60, No.3, pp 241-251.*

Technical publications of PI(s)

11. Sivasuthan, S., Karthik, V., Rahunanthan, A., Jayakumar, P., Thyagarajan, R., Udpa, L., and Hoole, S. (2015) “Addressing Memory and Speed Problems in Nondestructive Defect Characterization: Element-by-Element Processing on a GPU". *Journal of Nondestructive Evaluation (Springer), Vol. 34, No. 2*
12. Parthasarathy, M., Kosarek, P., Santini, J., Thyagarajan, R. (2015) “Methodology Development of Computationally-Efficient Full Vehicle Simulations for the Entire Blast Event”. *NDIA Ground Vehicle Systems Engineering and Technology Symposium (GVSETS) Modeling & Simulation, Testing and Validation (MSTV) Mini-Symposium August 4-6, Novi, Michigan. DTIC Report # AD A626806*
13. Mathialakan, T, Karthik, VU, Jayakumar, Paramsothy, Thyagarajan, Ravi, Hoole, S Ratnajeevan H (2015) “The Depth Limits of Eddy Current Testing for Defects: A Computational Investigation and Smooth-Shaped Defect Synthesis from Finite Element Optimization”. *International Journal of Materials and Manufacturing, Paper No. 2015-01-0595, pp 450-457.*
14. Karthik, V., Mathialakan, T., Jayakumar, P., Thyagarajan, R., Hoole, S. (2015). “Coil positioning for defect reconstruction in a steel plate”. *Presented at the IEEE 31st International Review of Progress in Applied Computational Electromagnetics (ACES), March.*
15. Sivasuthan, S., Karthik, V., Rahunanthan, A., Jayakumar, P., Thyagarajan, R., Udpa, L., and Hoole, S. (2015) “A Script-based, Parameterized Mesh Generator Library for Coupled Gradient Design and NDE". *IETE Technical Review, Volume 32, No.2, pp 94-103*
16. S. Ratnajeevan H. Hoole, Victor U. Karthik, Sivamayam Sivasuthan, Arunasalam Rahunanthan, Ravi S. Thyagarajan and Paramsothy Jayakumar (2015). “Finite Elements, Design Optimization, and Nondestructive Evaluation: A Review in Magnetics, and Future Directions in GPU-based, Element-by-Element Coupled Optimization and NDE”. *DTIC Report # AD A589531. International Journal of Applied Electromagnetics and Mechanics, Volume 47, No.3*
17. Masmoudi, A., Karthik, V U., Sivasuthan, S., Rahunanthan, A., Thyagarajan, RS., Jayakumar, P., Udpa, L., Hoole, S R H (2015). “Faster, more accurate, parallelized inversion for shape optimization in electroheat problems on a graphics processing unit (GPU) with the real-coded genetic algorithm”. *COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, Volume 34, No.1, pp 344-356.*
18. Sherri Chandra, Jaisankar Ramalingam, Ravi Thyagarajan (2014). “Reduced Order Modeling for Rapid Simulations of Blast Events of a Military Ground Vehicle and its Occupants”. *NDIA Ground Vehicle Systems Engineering and Technology Symposium (GVSETS) Modeling & Simulation, Testing and Validation (MSTV) Mini-Symposium August 12-14, Novi, Michigan. DTIC Report # AD A609195.*

Technical publications of PI(s)

19. Hsieh, C., Sheng, J., Thyagarajan, R., Akers, S., Korson, C., Ramalingam, J. (2014). “Development and Validation of EPH Material Model for Engineered Roadway Soil”. *NDIA Ground Vehicle Systems Engineering and Technology Symposium (GVSETS) Modeling & Simulation, Testing and Validation (MSTV) Mini-Symposium August 12-14, Novi, Michigan. DTIC Report # AD A608445*
20. Jiang, Weiran, Nickolas Vlahopoulos, Matthew P. Castanier, Ravi Thyagarajan, and Syed Mohammad (2014) "Reducing Structural Weight and Increasing Protection in Simple Structures Subjected to Blast Loads." *NDIA Ground Vehicle Systems Engineering and Technology Symposium (GVSETS) Modeling & Simulation, Testing and Validation (MSTV) Mini-Symposium August 12-14, Novi, Michigan. DTIC Report Number: AD A612781.*
21. Weed, R., Bessette, G., Thyagarajan, R. (2014). “Improvements to the Sandia CTH Hydro-Code to Support Blast Analysis and Protective Design of Military Vehicles”. *NATO/STO AVT-221 Specialists Meeting on "Design and Protection Technologies for Land and Amphibious NATO Vehicles", Copenhagen, Denmark, Apr 07-10, 2014. DTIC Report Number: AD A603852*
22. Babu, V., Thyagarajan, R., Arepally, S. (2014). “Retractor-Based Stroking Seat System and Energy-Absorbing Floor to Mitigate High Shock and Vertical Acceleration”. *NATO/STO AVT-221 Specialists Meeting on "Design and Protection Technologies for Land and Amphibious NATO Vehicles", Copenhagen, Denmark, Apr 07-10, 2014. DTIC Report Number: AD A603853*
23. Kulkarni, K., Ramalingam, J., Thyagarajan, R. (2014). "Assessment of the Accuracy of Certain Reduced Order Models used in the Prediction of Occupant Injury during Under-Body Blast Events," *SAE Int. J. Trans. Safety 2(2):2014, doi:10.4271/2014-01-0752*.
24. Sivasuthan, S., Karthik, V., Rahunanthan, A., Thyagarajan, R. (2014) Jayakumar, P., and Hoole, S., "The Finite Element Method in Optimization: The Forking of Already Parallelized Threads on Graphics Processing Units to Realize Speedup". *Paper No. ACES2014-1187, Proc. 30th International Review of Progress in Applied Computational Electromagnetics, Jacksonville, Florida. March. Also published in Applied Computational Electromagnetics Society Journal, Vol. 29, No. 9*
25. Chris Hoppel, Scott Kukuck, Ravi Thyagarajan *et al* (2014). “Workshop on Numerical Analysis of Human and Surrogate Response to Accelerative Loading: Final Report”. *DTIC Report # AD A604517, Army Research Lab Scientific Report ARL-SR-287*
26. Thyagarajan, R., Ramalingam, J., and Kulkarni, K.B., (2014). “Comparing the Use of Dynamic Response Index (DRI) and Lumbar Load as Relevant Spinal Injury Metrics”. *ARL Workshop on Numerical Analysis of Human and Surrogate Response to Accelerative Loading, Jan 7-9, Aberdeen, MD. DTIC Report # AD A591409.*

Technical publications of PI(s)

27. Victor U. Karthik, Sivamayam Sivasuthan, Arunasalam Rahunanthan, Ravi S. Thyagarajan, Paramsothy Jayakumar, Lalita Udpa and S. Ratnajeevan H. Hoole (2014). “Inversion of Heavy Current Electroheat Problems on a Graphics Processing Unit (GPU). DTIC Report # AD A590028
28. Sivasuthan, S., Karthik, V., Rahunanthan, A., Jayakumar, P., Thyagarajan, R., Udpa, L., and Hoole, S. "GPU Computation: Why Element by Element Conjugate Gradients?" *Proc. 16th Biennial IEEE Conference on Electromagnetic Field Computation, Annecy, France.* May.
29. Kulkarni, K.B., Ramalingam, J., and Thyagarajan, R. (2013). “Evaluating the Effectiveness of Various Blast Loading Descriptors as Occupant Injury Predictors for Underbody Blast Events”. *NDIA Ground Vehicle Systems Engineering and Technology Symposium (GVSETS) Modeling & Simulation, Testing and Validation (MSTV) Mini-Symposium August 21-22, Troy, Michigan. DTIC Report Number: AD A590537.*
30. V Karthik, S Sivasuthan, A Rahunathan, P Jayakumar, Ravi Thyagarajan, and S Hoole (2013). “Finite Element Optimization for Nondestructive Evaluation on a Graphics Processing Unit for Ground Vehicle Hull Inspection*”. NDIA Ground Vehicle Systems Engineering and Technology Symposium (GVSETS) Modeling & Simulation, Testing and Validation (MSTV) Mini-Symposium August 21-22, Troy, Michigan. DTIC Report Number: AD A590124.*
31. Li, L., Stowe, N., Vlahopoulos, N., Mohammad, S., Barker, C., Thyagarajan, R. (2013). “Utilization of Fast Running Models in Buried Blast Simulations of Ground Vehicles for Significant Computational Efficiency”. *NDIA Ground Vehicle Systems Engineering and Technology Symposium (GVSETS) Modeling & Simulation, Testing and Validation (MSTV) Mini-Symposium August 21-22, Troy, Michigan, DTIC Report # AD A590114.*
32. Thyagarajan, R., Ramalingam, J., Kankanalapalli, S., Vunnam, M. (2013). “Multi-temporal Analysis of Underbody Improvised Explosive Device (IED) Theater Events on Ground Vehicles Moving in a Convoy using Modeling and Simulation (M&S)”, *DTIC Report # AD A619979.*
33. Richard Weed, Christopher Moore, Ravi Thyagarajan (2013). “Enhancements and Analysis of CTH Software for Underbody Blast”. *DTIC Report # AD A571176, March.*
34. Jaisankar Ramalingam, Sherri Chandra, Ravi Thyagarajan (2013). “Reduced Order Modeling for Rapid Simulations of Blast and Rollover Events of a Ground Vehicle and its Occupants Using Rigid Body Dynamic Models”. *DTIC Report # AD A585048, March.*
35. J. Jablonski, P. Carlucci, R. Thyagarajan, B. Nandi, and J. Arata (2012). “Simulating Underbelly Blast Events using Abaqus/Explicit – CEL”. *2012 SIMULIA Customer Conference, DTIC Report # AD A571166, May*.
36. Richard Weed, Christopher Moore & Ravi Thyagarajan (2011). “Implementation of ERDC HEP Geo-material Model in CTH and Application to Buried Explosives Simulations”. *Numerical Methods for Blast Effects, 82nd Shock and Vibration Symposium, Baltimore, MD, Oct 31 - Nov 3. DTIC Report # ADA5512.*

Technical publications of PI(s)

37. Daniel Dooge, Ramesh Dwarampudi, Grant Schaffner, Adam Miller, Ravi Thyagarajan, Madanmohan Vunnam & Venkatesh Babu (2011). “Evolution of Occupant Survivability Simulation Framework Using FEM-SPH Coupling”. *2011 NDIA Ground Vehicle Systems Engineering and Technology Symposium (GVSETS), DEARBORN, MI, Aug 9-11*. *DTIC Report # ADA547566.*
38. Ravi Thyagarajan (2010). “End-to-end System level M&S tool for Underbody Blast Events”. *27th Army Science Conference, Army Technology Showcase, Orlando, FL, Nov 29 – Dec 2.* DTIC Report # ADA550921
39. Mike Keranen, Srikanth Krishnaraj, Kumar Kulkarni, Li Lu, Ravi Thyagarajan & Velayudham Ganesan (2005). “Automating Instrument Panel Head Impact Simulation”. *Paper no. 2005-01-1221, 2005 SAE World Congress, Detroit, MI, Apr 11-14*. Also published in *The 2005 SAE Transactions* for its long term intrinsic value.
40. Micheal Keranen, Kumar Kulkarni, Jeff Stasevich & Ravi Thyagarajan (2004). “A Discussion on Interior Compartment Doors and Latches”. *Paper no. 2004-01-1483, 2004 SAE World Congress, Detroit, MI, Mar 8-11.*
41. Hong Su, Ravi Thyagarajan & Joel Brown (2004). “Virtual Key Life Tests of Instrument Panels for Product Development”. *Paper no. 2004-01-1482, 2004 SAE World Congress, Detroit, MI, Mar 8-11.*
42. Srikanth Krishnaraj, Vikram Narayanasamy, Ravi Thyagarajan, Rohit Jategaonkar & Ana Barbir (2003). “Comparison of Facet vs. Ellipsoid Dummies in Frontal Crash Simulations”. *TNO 2003 MADYMO Users’ Conference, Troy, Michigan, Summer.*
43. Hong Su, Ravi Thyagarajan & Joel Brown (2003). “Virtual Key Life Tests using CAE Methodologies for Instrument Panels*”. MSC 2003 Virtual Product Development (VPD) Conference, Dearborn, MI, Oct 13-15*
44. Srikanth Krishnaraj, Kumar Kulkarni, Vikram Narayanasamy & Ravi Thyagarajan (2003). “Occupant Knee Impact Simulations: A Parametric Study”. *Paper no. 2003-01-1168, 2003 SAE World Congress and Exposition, Detroit, MI, Mar 3-6.*
45. Nick McGuire, Sharon Madley & Ravi Thyagarajan (2002). “Vehicle Interior Design using RAMSIS and GENPAD ®”. *2002 RAMSIS User Conference Troy, MI, Sep 9-10.*
46. Nick McGuire, Sharon Madley, Sean Sevrence, Jim Kostrzewa, Jim Bilk, Diane Gourd & Ravi Thyagarajan (2002). “GENPAD ® - Ergonomic Packaging”, *Paper no. 2002-01-1241, 2002 SAE World Congress and Exposition, Detroit, MI, Mar 4-7.*
47. Ravi Thyagarajan (2001). “Process to Detect Initial Intrusion – The First Step for Rattle Detection”, *Docket No. V200-0954, Research Disclosure, RD-446074, June*
48. Ravi Thyagarajan & Kumar Kulkarni (2001). “Optimizing the Effects of Body Attachment Stiffness on Steering Column In-Vehicle Modes”. *Paper no. 2001-01-0041, 2001 SAE World Congress and Exposition, Detroit, MI, Mar 5-8*.

Technical publications of PI(s)

49. Ravi Thyagarajan & Kumar Kulkarni (2000). "Effects of Body Attachment Compliance on Steering Column In-Vehicle Modes*". Paper no. 2000-01-2692, IBEC-2000 International Body Engineering Conference, Society of Automotive Engineers, Detroit, MI, Oct 3-5*.
50. Akkerman, A., Thyagarajan, R., Stander, N., Burger, M., Kuhn, R., Rajic, H. (2000). "Shape Optimization for Crashworthiness Design Using Response Surfaces". *Proceedings of the 1st International Workshop on Multidisciplinary Design Optimization, Pretoria, South Africa, Aug 8-10, pp. 270-279*.
51. Ravi Thyagarajan, Alex Akkerman, Mike Burger, Nielen Stander, Bob Kuhn, & Hrabri Rajic (2000). "Shape Optimization of Instrument Panel Components For Crashworthiness Using Distributed Computing". *Paper no. 2000-01-2682, IBEC-2000 International Body Engineering Conference, SAE, Detroit, MI, Oct 3-5*.
52. Kumar Kulkarni, Jack Chu & Ravi Thyagarajan (1999). "Using CAE to Guide Material Selection Process in Automotive Interior Applications". *Paper no. 1999-01-3177, IBEC-99 International Body Engineering Conference, Society of Automotive Engineers, Detroit, MI, Sept 28-30*.
53. Alex Akkerman, Bob Kuhn, Hrabri Rajic, Nielen Stander & Ravi Thyagarajan (1999). "Optimization of Instrument Panel Crashworthiness". *Second European LS-DYNA Conference, Gothenburg, Sweden, June 14-15.*
54. C-J Chen, Mohammed Usman, David Bauer & Ravi Thyagarajan (1998). "Reduction of Instrument Panel Manufacturing Cost by Using Design Optimization". *Paper no. 982370, IBEC-98 International Body Engineering Conference, Society of Automotive Engineers, Detroit, MI, Sept 29-Oct 1*.
55. Ravi Thyagarajan & Kumar Kulkarni (1998). "A Brief Look at Instrument Panel Knee Bolster Designs and Materials". *1998 Society of Plastics Engineers (SPE) Regional Technical Conference, Interiors Exposition, Detroit, MI, May 21.*
56. Satish Pattanaik, Jared Clark, Jeff Sandula & Ravi Thyagarajan (1998). "Rapid CAE Analysis from Parametric Solid Model Assemblies of Instrument Panel Structures". *Paper no. 980388, 1998 SAE International Congress and Exposition, Detroit, MI, Feb 23-26.*
57. Ravi Thyagarajan, Scott Kuschinsky & Kumar Kulkarni (1997). "Computer Analysis in the Automotive Industry". *Automotive Engineering Magazine, Nov 1997, pp 49-55.* [Magazine article]
58. Joe Jira, Ravi Thyagarajan, & Kumar Kulkarni (1997). "Deformation Control with the Use of Unique Cowltop Attachments". *Automotive Body International Quarterly, Vol. 2 No.3, pp 27-32, Summer.* [Magazine article]
59. Ravi Thyagarajan, Scott Kuschinsky & Kumar Kulkarni (1997). "Using CAE to Guide Passenger Airbag Door Design for Optimal Head Impact Performance". *SP-1226, pp 143-146, 1997 SAE International Congress and Exposition, Detroit, MI, Feb 24-27.*

Technical publications of PI(s)

60. Joe Jira, Ravi Thyagarajan & Kumar Kulkarni (1996). “Deformation Control in Automotive Instrument Panels Exposed to High Sunload Temperatures With the Use of Unique Cowltop attachments”. *Paper no. 970772, International Body Engineering Conference (IBEC '96) Detroit, MI, Oct 1-3.*
61. Ravi Thyagarajan and Iwan, W.D. (1990). “Performance Characteristics of a Widely Used Hysteretic Model in Structural Dynamics.” *Proceedings of the 4th U.S. National Conference on Earthquake Engineering, Vol. 2, pp 177–186, Palm Springs, CA.*
62. Ravi Thyagarajan (1989). “Modeling and Analysis of Hysteretic Structural Behavior.” *Ph.D. thesis dissertation, Record: CaltechEERL:1989.EERL-89-03, California Institute of Technology, Pasadena, CA*
63. Gregory Thomas Hedderly, Robert Daniel Restauri, Michael Patrick Rodgers, William L. Fisher, Kumar Balakrishna Kulkarni, Thomas Junior, William Francis Weber: Patent # 6152489: “The integrated steering column and IP structure apparatus,” Nov. 2000
64. Douglas Michael Cappabianca, Dale Paul Moore, Joseph A. Bollo, Kumar Balakrishna Kulkarni, Ravi Thyagarajan, Venkat Reddy: Patent # 6474687: “One piece knee bolster,” Nov. 2002
65. Douglas Michael Cappabianca, Joseph Anthony Camilletti, Zhenjian Huang, Kumar Balakrishna Kulkarni, Mark M Sheldon, Mark Allen Turner: UK Patent GB 2 425 097 B: “Energy absorbing structure,” 21.3.2007

Responses to NAS Questions

What related research has been or is being performed elsewhere?

In the commercial auto industry and academia, and elsewhere within the US Army, topology optimization methodology is used to reduce weight when the actual service loads on a component are readily available. (Slides 2,3)

How does the project reflect an appropriate research niche that the Army is best suited to address?

The current advances in the area of Additive Manufacturing enable manufacture of complex free-forms that naturally occur after topology optimization with significant weight savings. Topology optimization multiplied with additive manufacturing offers significant light-weighting opportunities, often even with improved structural performance.

Development of a service-load-agnostic method of component design optimization is a niche research need for the Army

What is the research approach?

The approach is broadly based on combining the SIMP (Solid Isotropic Material with Penalization for intermediate densities) method, with Gradient-based optimization algorithms capable of handling large number of continuous variables and multiple constraints. (Slides 4,5,10)

What are the research hypotheses?

Under the assumption of over-designed structures with significant dead weight, which is largely true for military ground vehicles, the hypothesis is to obtain suitable performance targets from the existing baseline component itself as design criteria for the optimization problem. These are service load-agnostic and based on compliances, strength and modal properties of the current part. (Slides 6,7)

Responses To NAS Questions

What methods of data collection (laboratory experiment, modeling, field experiment, survey, etc.) are being used and why?

Modeling and numerical simulation techniques using modified finite element based topology optimization tools which are widely available. Once the models are generated, simulations are performed on DoD's High Performance Computers.

What specific equipment or tools are being employed in the research?

See above. Specifically, a commercially available software called Optistruct from Altair Inc. is used in this research project. Simulations are performed utilizing DoD Supercomputing Resource Centers (DSRCs)

What analyses of data are being applied to determine results, and why?

We use standard data analytics and post-processing of finite element analysis (FEA) results. The resulting "raw" shapes from the topology optimization are then refined to create feasible designs, and then performance-validated against the baseline design to ensure success.

What are the results to date?

Optimized designs have not only met but *exceeded* targets for stiffness (+10% avg) & strength (+32% avg) in all directions and first three natural frequencies (+16% avg), set by the original design. At the same time, we have achieved a 15% reduction in weight for these designs.

How do the results fit with expectations and with results found previously or by others?

From a general viewpoint, these findings are similar to those efforts conducted with knowledge of service loads. A comparison of this very same component at University of Michigan [7] yielded similar weight savings.

However, there are no known research efforts being done elsewhere without knowledge of loads, so no direct comparison can be made.

Responses To NAS Questions

What conclusions have you drawn from the results?
A proof of concept modeling and simulation strategy has been shown on a component design, demonstrating feasibility and identifying potential weight save opportunities (Slide 16).

What future research direction do you intend to pursue?

1. Perform constraint perturbations (+/-10%) and investigate relationship between weight savings and constraints.
2. Determine the feasibility of this approach to develop blended solid and lattice structures to exploit additional weight savings (such structures are highly 3D-printer friendly).
3. Validate this methodology on a different component/sub-system. Characterize identifiable characteristics of a part that enable weight savings with minimal loss of performance.

Are there any points on which you are challenged and are seeking assistance?
None at this time.

Are there collaborators involved in the project? If so, what are their roles and contributions and that of the RDEC researcher?
None, other than the two listed PIs

How much of your time is allocated to the project?
30% for PI#1, 5% for PI#2

Is the research limited by resources of staff, equipment, opportunities to publish, or other factors?
Not at this time

Responses to NAS Questions

Who reviews the technical quality of your research? With whom do you discuss the progress of your research?

1. At the time that the ILIR project is selected for initial or continued funding, the reviewers also provide feedback to the proposal, which are then incorporated to the extent possible.
2. The Office of Chief Scientist, US Army, TARDEC and the Senior Technical Experts (STEs) from the various tech areas in TARDEC perform a mid-year review of all ILIRs
3. At the end of every year, we write a Final report, this is reviewed both internally by STEs and by an external academic reviewer/SME. Based on that feedback, we modify the Report as well as future research direction.
4. The Final report is then submitted to RDECOM and then onto ASA/ALT, and any feedback from those reviews are also considered, if provided.

We also discuss progress informally with our colleagues, STEs, etc., often using them as sounding boards rather than as formal stage gate reviewers.

What publications and/or presentations have emerged from the research?

A technical paper is being submitted for the 2019 Ground Vehicle Systems Engineering and Technology Symposium (GVSETS)