Generalized Synthesis Methodology of Nonlinear Springs for Prescribed Load-Displacement Functions

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Nonlinear Spring Applications

Statically Balanced Mechanisms

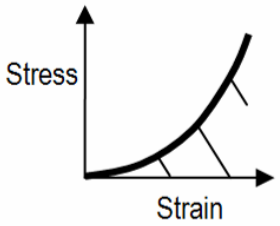
Design for crashworthiness

Constant-force Springs

MEMS Devices

Human Interfaces (Comfort, Tactile)

Nature's Nonlinear Compliance



Artificial Implants and Prosthetics

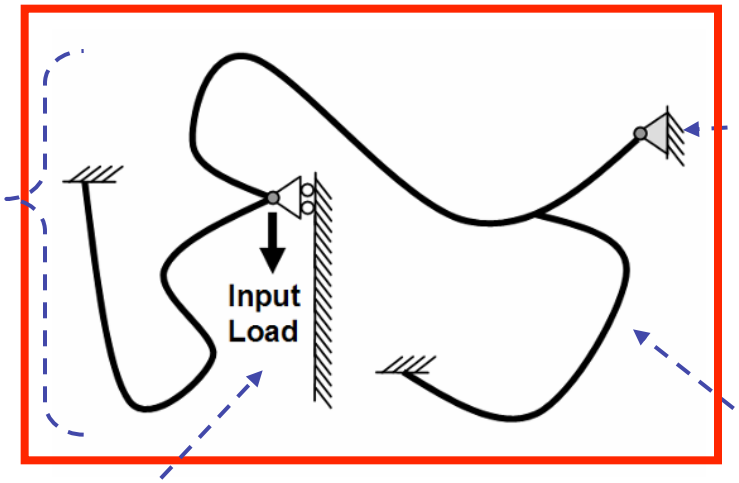
- Structures with synthesized nonlinear elasticities
- Mimic nonlinear and viscoelastic materials

Freedom Innovations

Otto Bock

Nonlinear Spring Parameterization

A typical nonlinear spring design



Network of splines
- For generating any nonlinear response

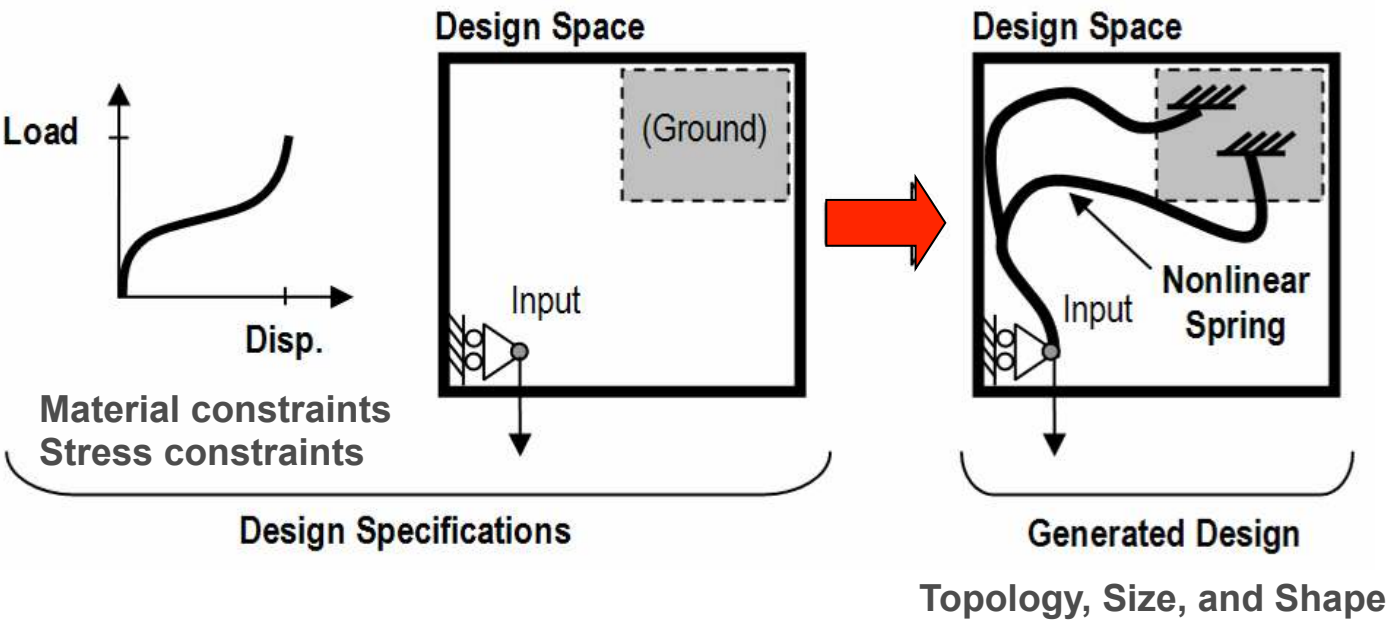
Pinned end conditions
- For large rotations and minimal bending stresses

Input constrained along path
- Forces spring to stretch/compress (axial mode)

Curvilinear members
- Longer effective length
- Greater strain energy absorption
- Larger displacements and rotations
- Fewer stress concentrations

Problem Statement

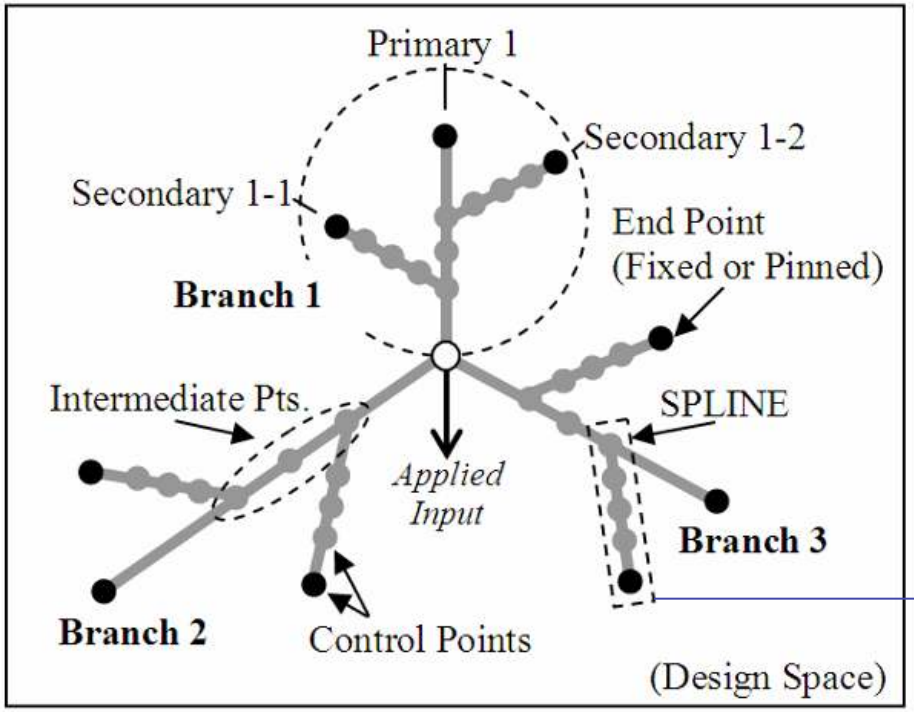
- Problem Statement



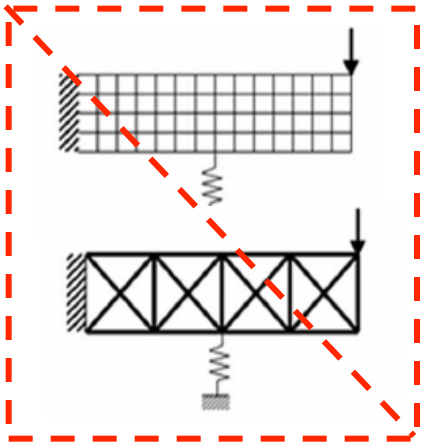
- Scope
  - Planar springs
  - Elastic range
  - No buckling

New Design Parameterization

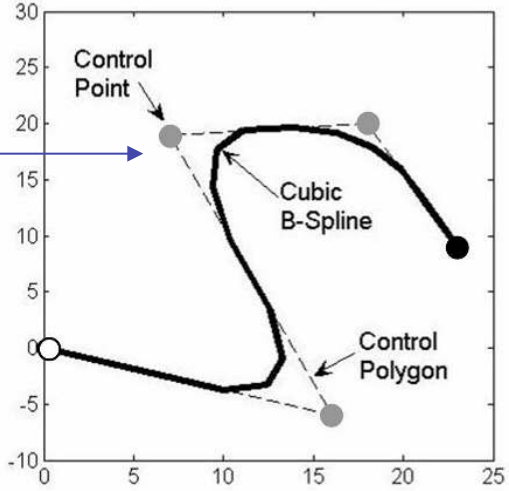
- Topology



9 Splines
(3 Primary, 6 Secondary)



B-SPLINE



New Design Parameterization

- Each design has 96 variables that describe…

Topology

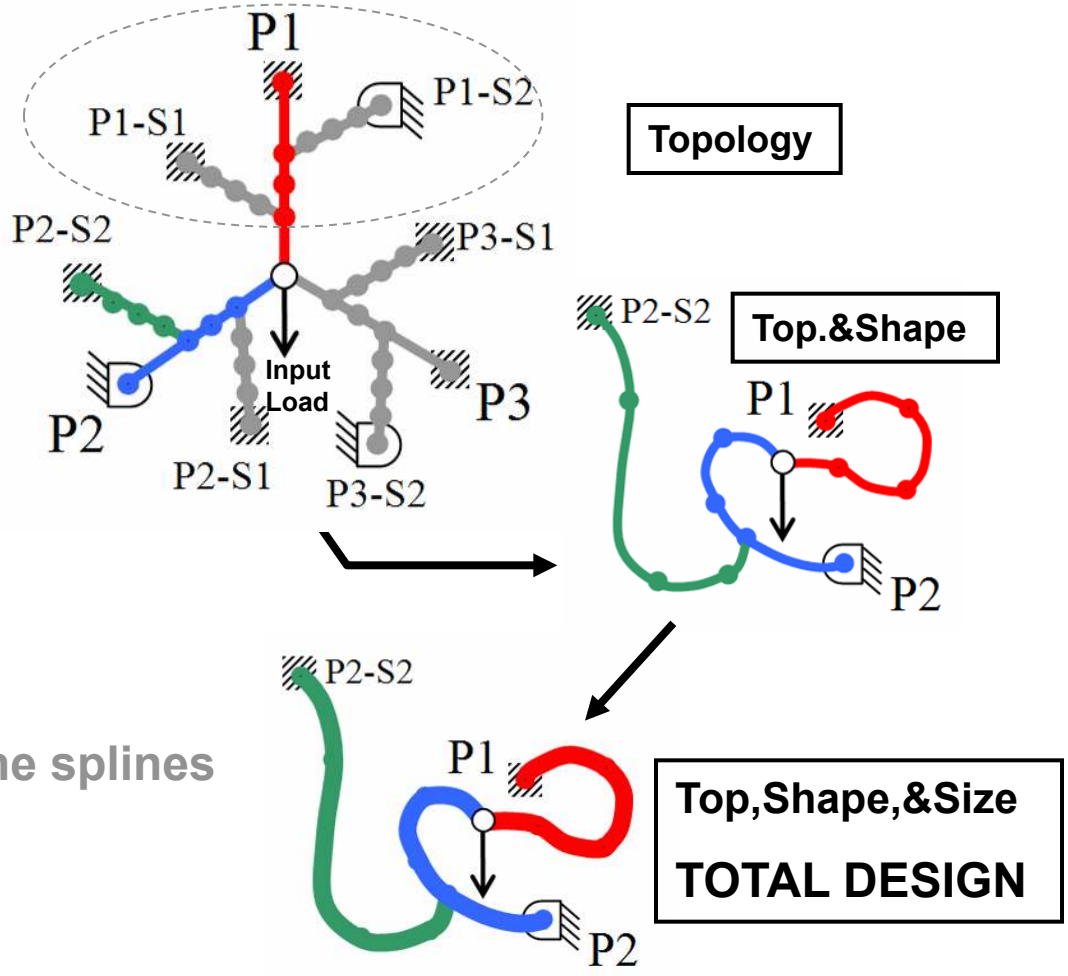
- Number of splines
- Connection of splines
- Boundary conditions

Shape

- Shape of the splines

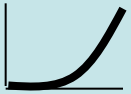
Size

- In-plane thickness of the splines

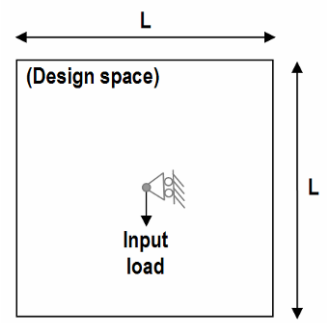


Design Examples

3 Nonlinear Springs (+ 1 Linear Spring)

Shape-function	J-curve 	S-curve 	Constant-force 
Load-range	10N	75N	150N
Displacement-range	20mm	80mm	150mm
N_{up} (Scaling)	1.2	1.5	2.0
Square design space size (L)	100mm (10cm)	500mm (0.5m)	1000mm (1m)
Material modulus (material)	115MPa (Titanium)	115MPa (Titanium)	70MPa (Aluminum)
Maximum stress (safety factor)	830MPa (1)	415MPa (2)	275MPa (1)
Out-of-plane thickness	4mm	20mm	60mm
In-plane thickness	0.4-0.7mm	1-3mm	2-5mm

Design Space



Genetic Algorithm

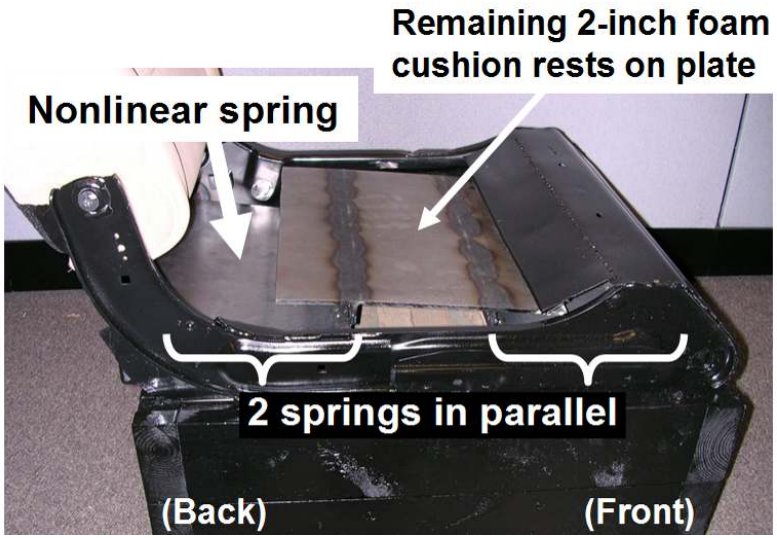
Population: 96

Crossover rate: 70%

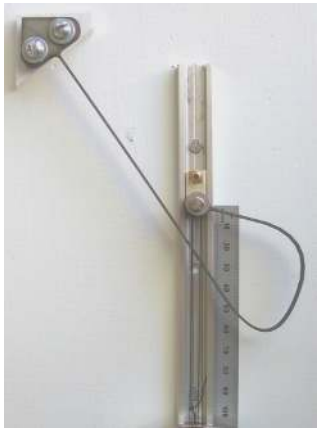
Mutation rate: 3%

Nonlinear Spring Applications

- Automotive seat cushion (hardening spring)



- Constant-force applications (softening spring)



Un-deformed

Deformed

Automotive Seat Cushion

4-inch foam cushion (Expensive to store and ship)

EQUIVALENT LOAD-DISPLACEMENT FUNCTIONS

4 Inches of Foam
+
Rigid Seat Pan

Current Design

=

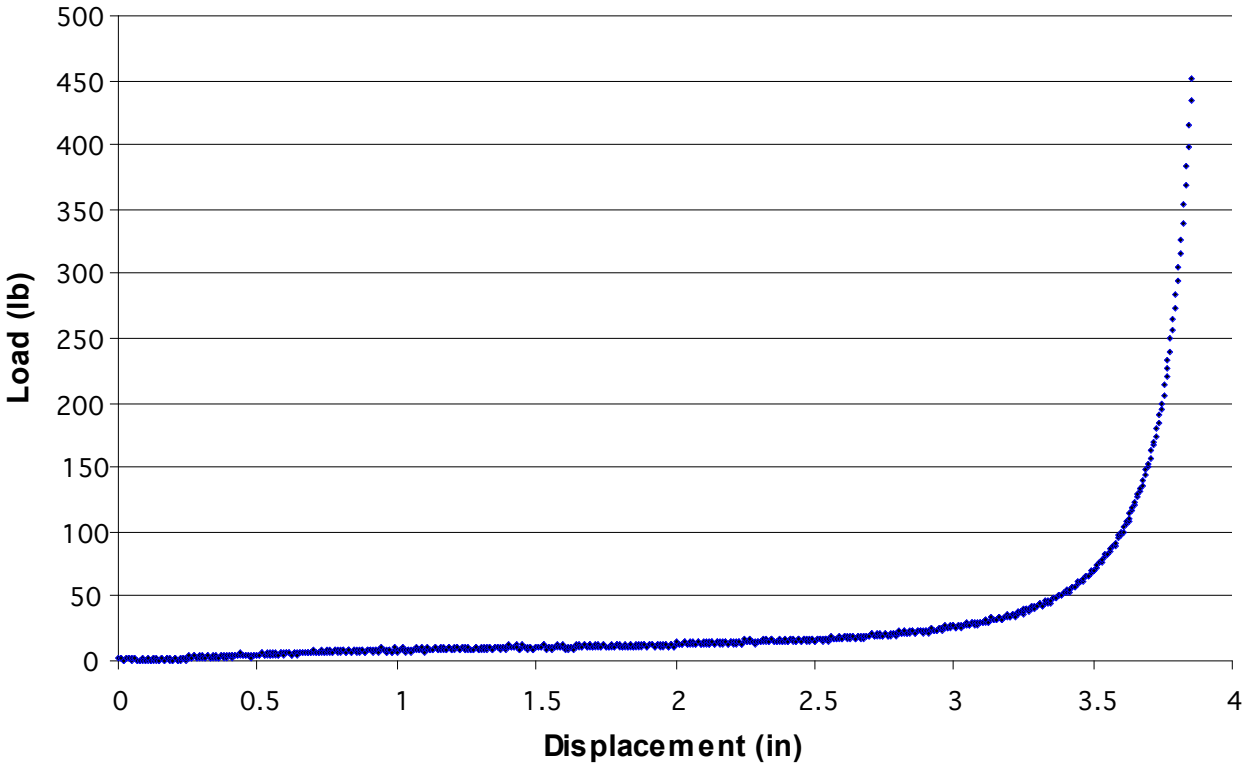
2 Inches of Foam
+
Compliant Seat Pan
(Nonlinear Mechanism/Spring)

New Design

Rigid Seat Pan
Multi-piece stamped and welded steel pan
(No foam or cover shown)

Ford Land Rover

Passenger Comfort

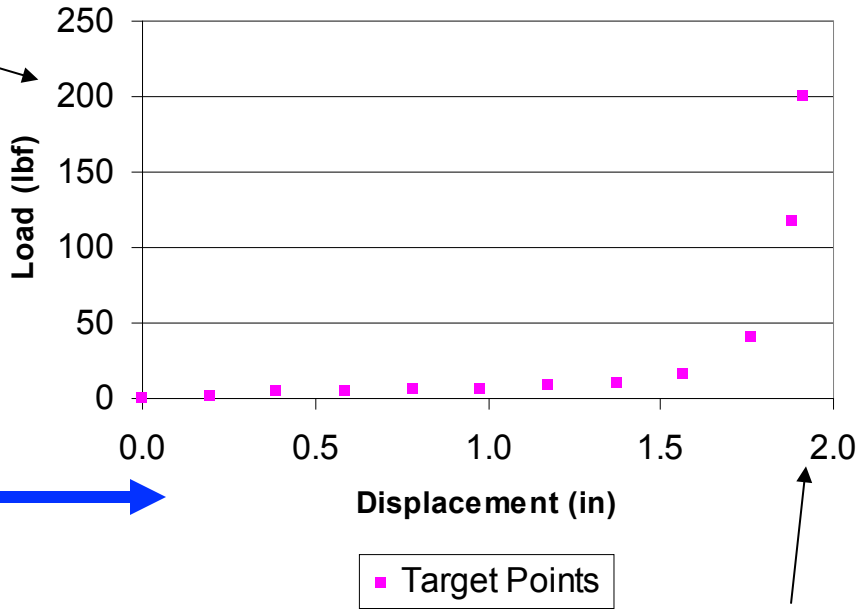


Ford's force-displacement data measured at the center of the seat cushion. [1]

4-inch foam cushion

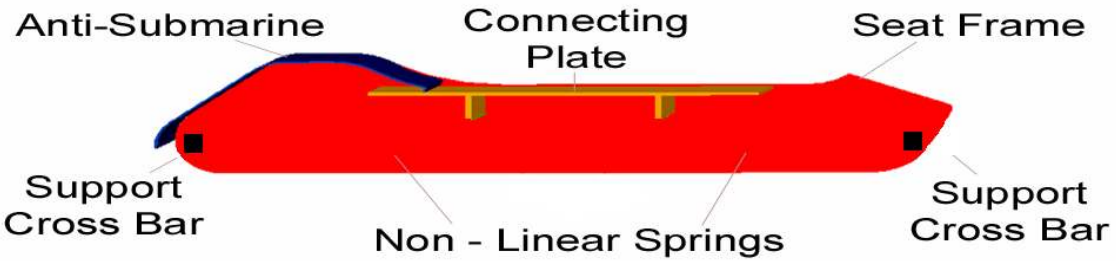
Problem Definition

Spring in *Parallel*



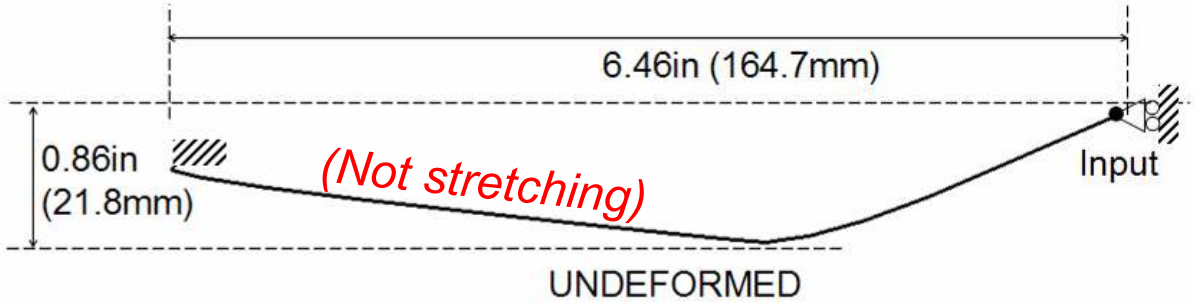
Design a nonlinear spring:
1) Match load-displacement function
2) Fit within prescribed design space

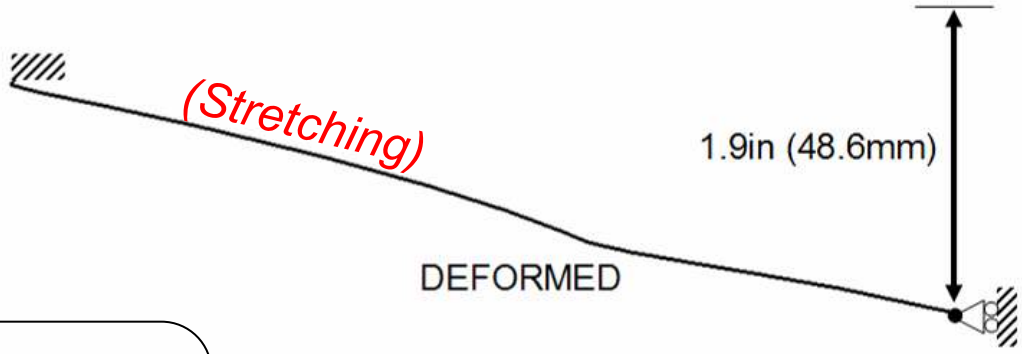
Spring in *series* with foam



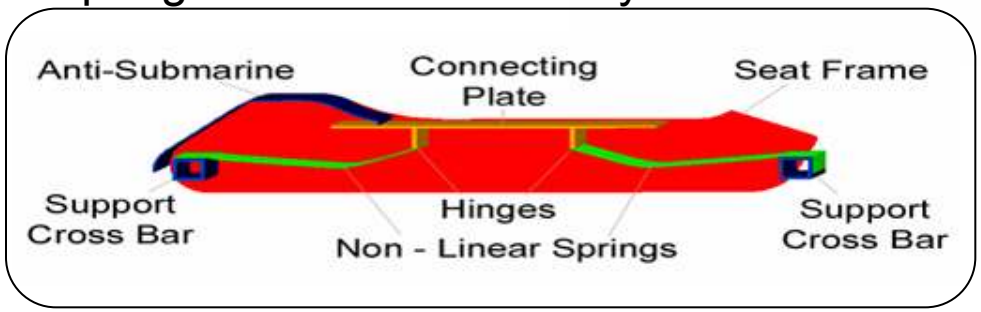
Functional Description

Final Spring Design





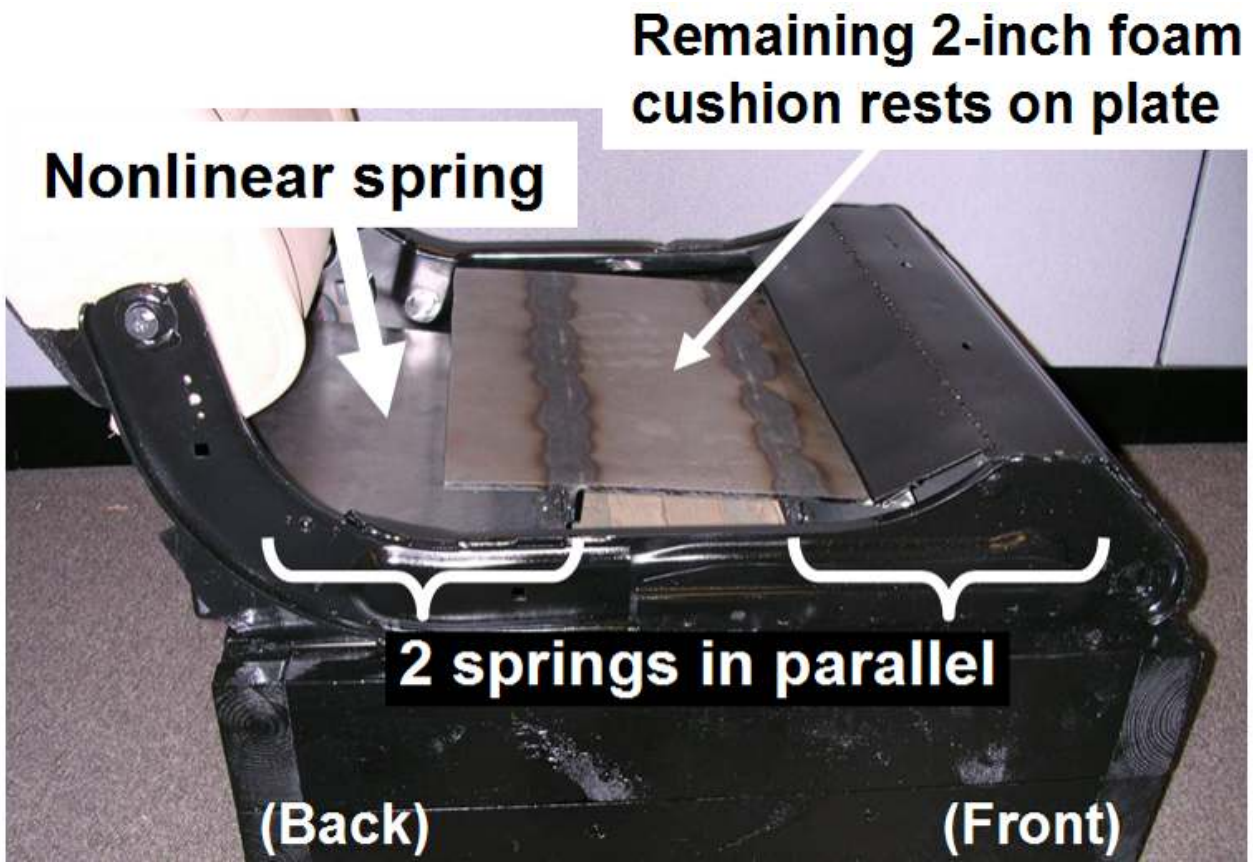
Spring within new assembly



In-plane thickness = 0.027in (0.69mm)
Out-of-plane thickness = 12in (304.8mm)
Material = MartINsite M130 (E = 200 GPa)
Max stress = 605MPa (< yield 930 MPa)
Safety factor =1.5
Disp. = 29% of largest footprint dimension

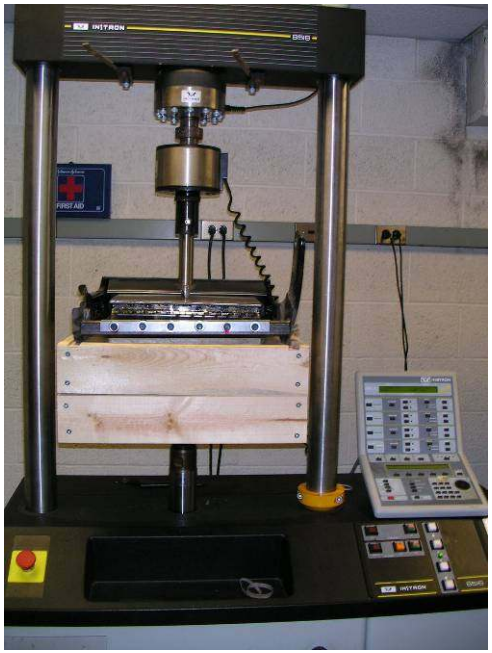
Functional Description

Final Spring Design's Assembly in Prototype

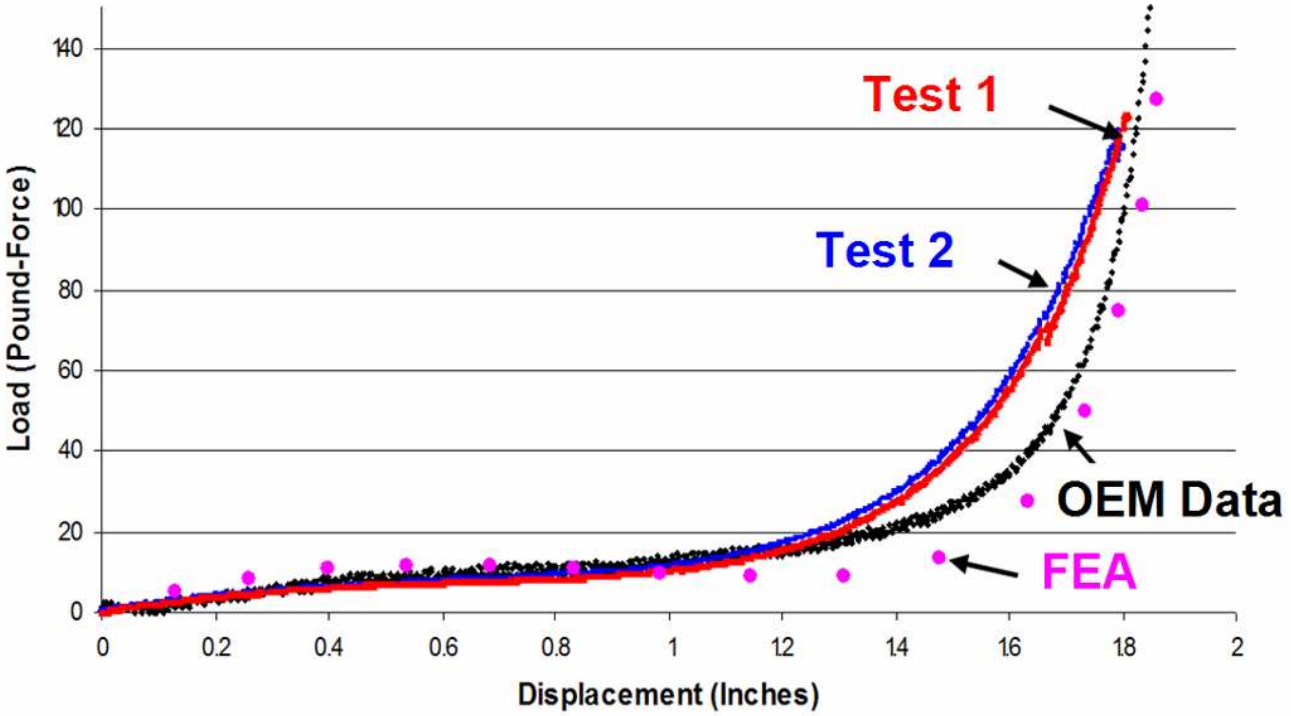


Functional Design

Validation



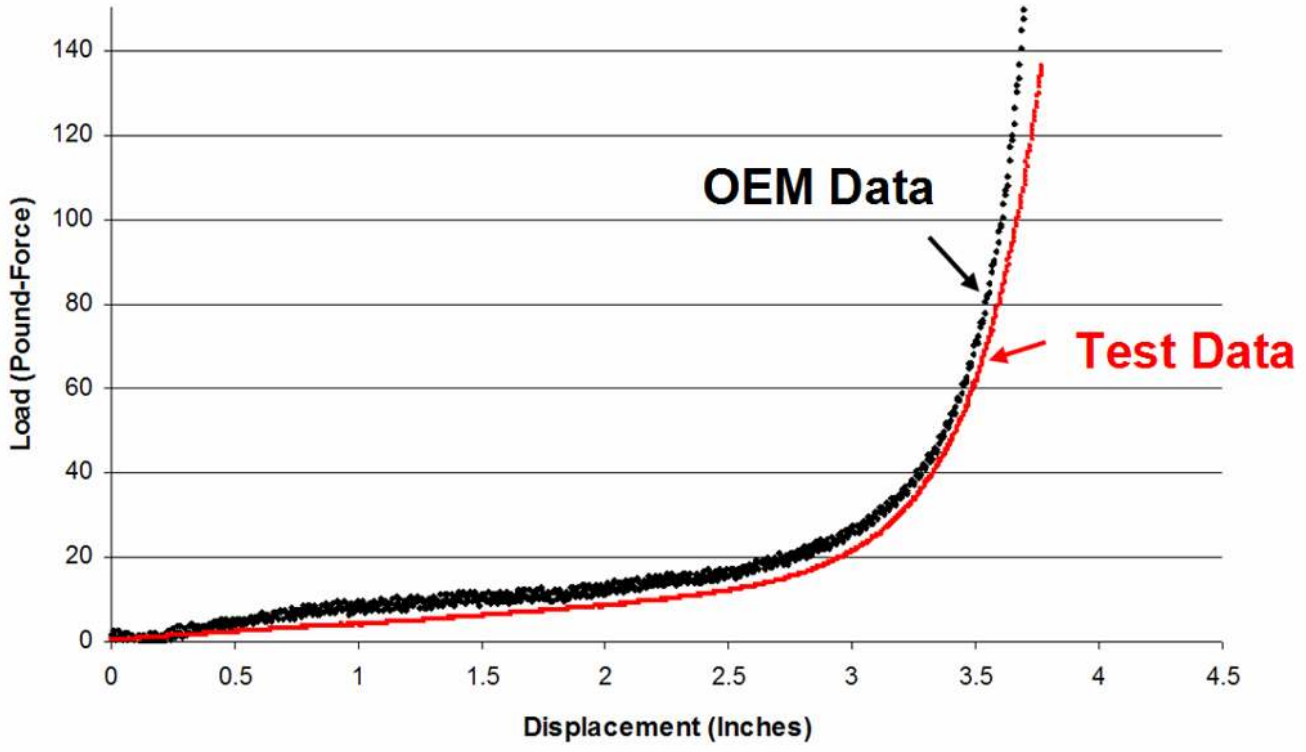
Instron 8516



Nonlinear spring assembly (No foam included)

Functional Design

Validation (Instron 8516)

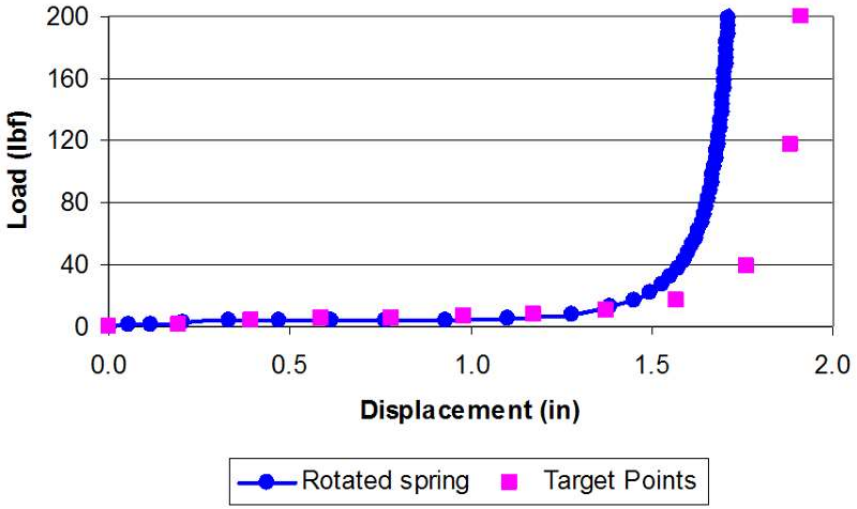


Nonlinear spring assembly (Foam included)

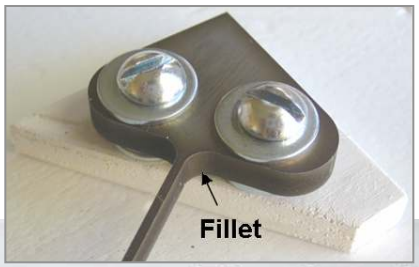
Conclusions

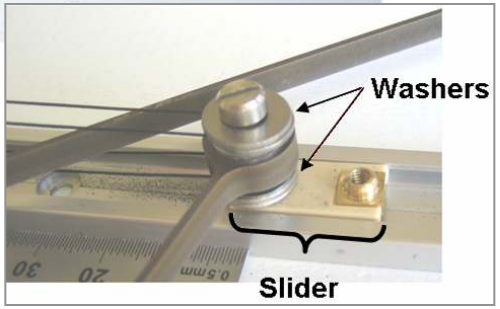
- Specifications where met only using 2-inches of foam
- Prescribed load-displacement function is sensitive to buckling
  - Original FEA design slightly buckled
  - Prototype did not buckle
    - Rotation of spring 2° accounts for discrepancy

- No buckling
- Shorter displacement-range



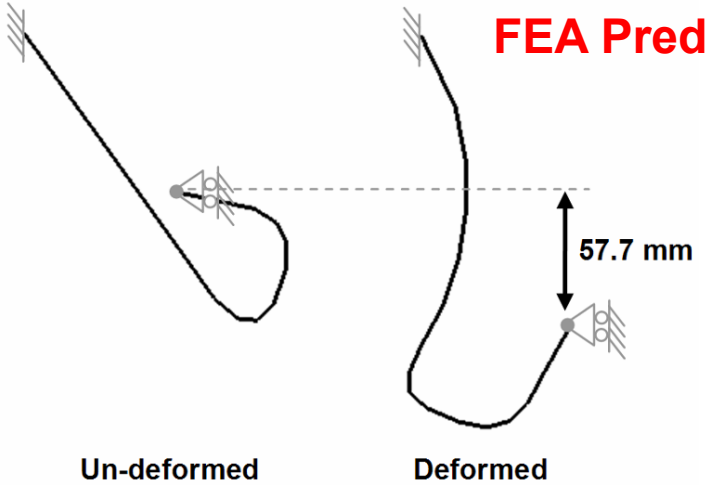
Test Assembly



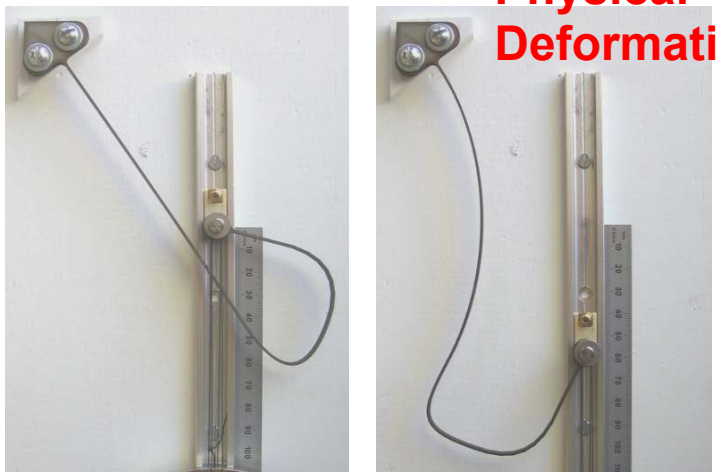


Results

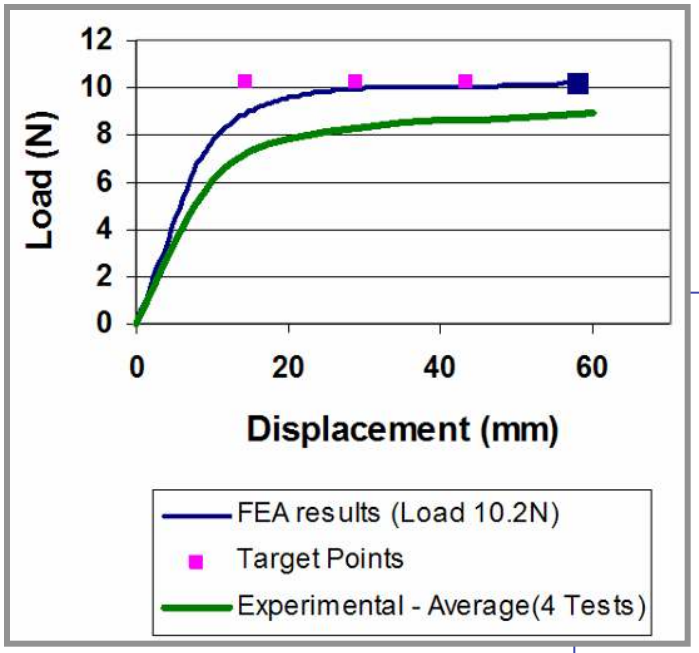
FEA Prediction



Physical Deformation

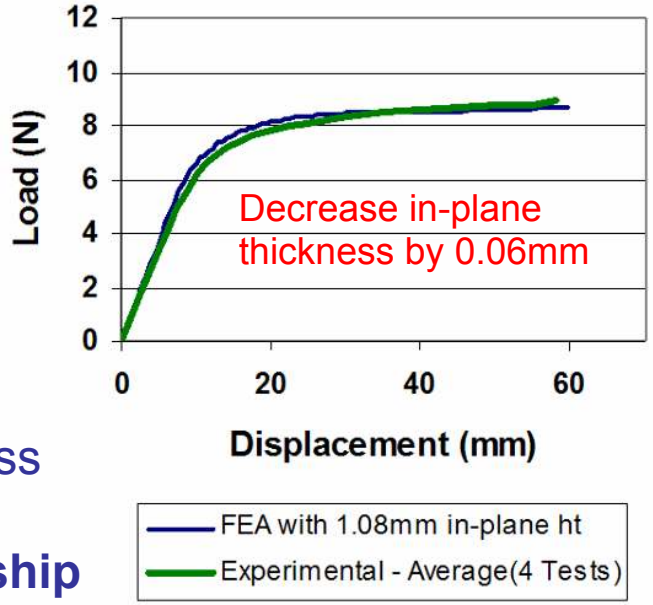


Results and Conclusions



Validated:
Deformation
Shape function
Displacement-range

Inconsistency:
Load-range (15%)



In-plane thickness and load have **cubed relationship**