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Design Improvement for Realistic Applications by Topology and Shape Optimization Technique

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ABSTRACT

Cost is always a driver for any manufacturer and as a steel weldment grows in complexity, the cost of the finished component also becomes complex. With a cost effective casting, you can use the process to your benefit. Where in a weldment you may be stuck with a certain sheet thickness because of a localized yield strength issue. Casting designs allow the designer more freedom in the part design than a weldment. The design can be very fluid and conform to almost any shape.In a casting you can locally thicken or make thin as needed, giving you a stronger, lighter and cheaper part for the application. As well castings generally have equivalent fatigue properties when compared to a fabricated design. In this study, a software tool that works on topology optimization principle is used to conclude the actual material distribution in the selected benchmark design. In other words, with this optimization, users can see the ideal part design (based on loading conditions) before moving into the CAD phase of the design process. This not only saves time (less failed prototypes/redesigns), but also decreases material usage and money. Results obtained from this technique will be refined by shape optimization using CAD software to create the manufacturability design. Then a static structural analysis is performed using ANSYS to compare the stress distribution in weldment and casting designs. This methodology of design optimization will help in reducing the design time and cost by producing quality product.

Keywords: weldment, casting, topology optimization, analysis

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I. INTRODUCTION

A common problem in weldment is durability due to strength concerns where the pieces are welded together. So in an enterprise product development process cycle, a weldment design needs to be converted or optimized to casting design with more iteration in the design phase which depends on the analysis inputs from finite element methods. These process steps consume more design time and in turn design cost.Benefits of converting weldment to casting design are as follows: (1) Improved durability by increased design strength (2) Reduction in number of parts in the assembly (3) Reduced process complexity (4) Reduced process time for product development (4a) Overall less labor time (4b) Time until Part is Ready (5) Better Mechanical Properties (6) Better Appearance (7) Saving cost by product design and process. Although some of the demerits include Initial Pattern Cost and Possible surfaces that will require machining. There exists a huge scope for optimizing design which can be described as follows.

Examination of a weldment for potential casting conversion also provides an opportunity to optimize the component's design. During this activity, the design can be optimized for load-carrying capability. There are number of techniques/methodology available for optimizing any product/process. Our focus is on optimizing the design at conceptual phase of product development cycle.

The basic problem that can be seen as a GAP in the conventional CAD based design development is that the number of design iterations required finalizing the design in which each iterationsis a result of feedback from analysis (finite element method).The impact is time consuming and high process cost.

One of the best process improvement solution is implementing a topology optimization driven design development, where all the load conditions along with design & manufacturing constraints are incorporated beforehand, which are required for proposing different conceptual options which would possibly result in first time right design.

1.1Topology & Shape Optimization

The topology optimization method solves the problem of distributing a given amount of material in a design domain subject to load and support conditions, such that the stiffness of the structure is maximized. It is used in the concept and predesign phase of the component design process and reduces product development times by generating an optimal load compatible initial layout design.

The procedure for topology optimization consists of the following main steps. (1) Define the problem (2) Select the element types (3) Specify optimized and non-optimized regions (4) Define and control the load cases
(5) Define and control the optimization process and
(6) Review results.

Non-parametric topological and shape optimization techniques are applied before 'locking' the design down to a 3D parametric model. This can lead to both greater innovation and reduced development time at the concept stage.

Today, all the modern manufacturing enterprises are striving to develop best optimized reduced weight and cost effective products that meet the intended design functionality and reliability. In this scenario, structural optimization tools like topology and shape optimization with manufacturing simulations are becoming attractive in product design processes. These tools also aid in reducing product development times. In last few years, topology optimization has emerged as the valuable tool to develop new design proposals especially in automobile and aircraft industries. Topology optimization calculates the optimal loads compatible design, under specified boundary conditions and constraints. This result in an innovative design proposal irrespective of dependency of the designer experience and conventional design approaches.

Many optimization approaches and codes have been developed and interfaced with commercial FE solvers, for example, FE-Design has interfaces with solvers ABAQUS, ANSYS, IDEAS and MSC. Marc, Altair OptiStruct uses Altair Hyper Works, ANSYS software topology optimization application, TOSCA with the ANSYS interface etc. Besides the limitations and inherent problems of topology optimization, an optimal new design proposal can be obtained with accurate loading and support positions on the model, which is developed as the initial design space. For topology optimization, commercial software determines an optimal placement of a given isotropic material of a reference domainΩ in space, in form of optimal subset of material points $\Omega_{mat}$and voids. For continuum structures, topology optimization is generally formulated and solved by considering the material distribution approach. In a defined domain, each finite element is assigned a variable density variable ρ. During optimization process, this variable density variable is assigned a value that ranges from 0 to 1. Elements with density variables having a value assigned as $\rho=0$ means voids at those locations in the initially designed domain. This is called a material distribution topology optimization problem based on maximum stiffness formulation or minimum global compliance. Considering (P) as the total elastic energy, optimization problem for a single load case can be defined as:

Minimize P Where r=1, 2… n
ρ_r
Subjected to: $\Sigma \rho_r V_r = V_o$
$0 \leqslant \rho_r \leqslant 1$ Where r=1, 2… n
n = total no of finite elements
V_o = Volume of initial design domain
V_r= Volume associated with an element

In ANSYS objective function (f) is minimized or maximized subject to the given constraints g_j. A design variable $\eta_i$is assigned to each finite element (i). Where,η_i denotes an internal pseudo density, the value of which varies from 0 to 1. An element with zero $\eta_i$means void at that location where the element exists in the reference domain, whereas number 1 represents material spot associated with that particular element. Mathematically;
Objective function:
f = Minimization/Maximization of compliance (that is external work w.r.t η_i)
Subject to:

$0 < \eta_i \leqslant 1$ (i=1, 2… N)

$\underline{g_j} < g_j \leqslant \bar{g}_j$

Where,
N = Total no of elements
M = No of constraints
$\underline{g_j}$= Computed jth constraint value
g_j= Upper bound of jth constraint
$\bar{g}_j$ = Lower bound of jth constraint

With structural optimization tools, computer simulations in CAE environment have also become indispensable in product design and development activities. At the design stage, via computer simulations a designer can better understand the product manufacturability that aids in the formulation of a better design.

In this paper, nonparametric topology optimization is applied to a simple weldment L-bracket with stiffener.

The first step is the development of a 3D model of initial design space, which defines the inner and outer boundaries within which material has to be arranged and optimized. Volumes and features that need not to optimize are clearly defined like fixed parts and supports of the component. Depending on the complexity of model, this can also be done in CAD software and then imported in CAE system. The next step is the mesh generation and change of attributes of elements of regions not to be optimized. Specifications needed for optimization process like objective function, constraints etc. are defined, and model is solved for topology optimization results. These results give a load compatible shape, consisting of a set of connected elements. The resulting model seems to be a rough non-geometry based design which is refined and smoothen by different approaches and then drawn back in CAD software. The model is also refined for various manufacturing and machining restrictions like minimum thickness requirements, aesthetic features, non-machineable areas, undercuts etc.

2 Literature Review

Literature 1: The research studies showed that steel castings have better fatigue properties than weldments for similar corner designs.Also, the corner designs produced as steel castings resulted in lower stress concentration than existed in comparable designs as produced by fabrication welding.The static loading studies showed that the L and box section designs as steel castings were stronger than the weldments.This study is focused on only corner designs between steel weldment and steel casting.

Literature 2: The paper explains about the effect of method of manufacture on the properties of steel. The study recommends that the design engineer who employs cast steel over steel weldments is allowed much more freedom in design areas. Example: Thick sections adjacent to thin sections can be easily made in steel castings whereas weldments are limited by the thickness of the rolled plate employed. Also greater structural rigidity is an inherent attribute of steel castings because of the design freedom resulting from local increasing of section thickness when necessary.

Literature 3: The paper explains about the merits of casting design over a 15 piece weldment design. In this application, the design is carried only by conventional method and only the material change has more impact on the life of the part which makes casting stronger than steel weldment. Still there is scope to optimize the design.

Literature 4: Some weldments and assemblies may be money–drains for OEMs. This article shows how to identify components worth considering as castings for possible savings.

Literature 5: This article highlights that the casting conversion (lower frame bracket by an AG manufacturer) resulted in reduced lead time and significant cost savings over a steel weldment.

Literature 6:This article highlights that the casting conversion (a primary mounting structure on a double disc ripper tillage unit) improves performance, strength and appearance by repositioning some of the metal compared to the original weldment.

Literature 7: This journal emphasis that the structural optimization methods create a high quality approximation based on physics (as opposed to simple linearization) to improve efficiency and robustness and then uses a general purpose optimizer to solve this approximate problem. The state of the art is well refined and is readily available in the commercial environment to improve design quality, reduce design time and increase corporate profits.

Literature 8: It is inferred that under the same loading conditions, constraints and intended design purposes, topology optimization results in better and more reliable design. A designer can produce the best optimized design without much dependency of his experience and previous design options and practices. The methodology adopted to design the component considering machining and manufacturing early at the design stage is very useful for robust and reliable design options.

Literature 9: In this paper a brief overview of mathematical foundations and pragmatic solutions of topology optimization approached with nonparametric structural optimization tools have been presented. An integrated design environment with nonparametric optimization, CAE and CAD system aids in finding the optimal design proposals.TOSCA optimization modules with data smoothing feature provide a comprehensive approach to find an optimal design proposal at the early design phase.Topology optimization can be used for dual purposes, to improve the existing designs and to find the novel design proposals.Topology optimization is an important tool to find the optimal design proposals with least possible times, because it reduces the overall product development cycle time.

Literature 10: Topology optimization and structural simulation helps a casting company develop better products faster.

Literature 11: The technology has been successfully used in an industrial environment with short industrial time scales and has on a single application proved to be able to provide efficient stress and stability component designs. Load definitions generally change as the design of an aircraft mature, and this could seriously affect the optimality of the structure. It could therefore prove important to carefully select applications for topology optimization and only use the technology on structures with well-defined loading conditions.

Literature 12: This paper provides information about how do you develop, optimize and produce a new part with the highest performance and lowest cost, without increased investment in simulation software.

Literature 13: This paper demonstrates the process that starts with load path study using Topology Optimization (Optistruct) & Parametric study using shape optimization (Hyper Morph) aids in cutting down the desire iteration and optimize the material and performance.

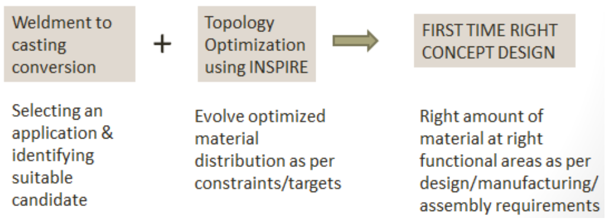
Literature 14: Hyper Works is helping Luxon Engineering remain in the forefront of simulation-driven design and is helping Luxon’s customers optimize their products to retain a competitive advantage.

2.1Conclusions and GAP Identification

- ✓ Study not carried for weldment with stiffeners.
- ✓ INSPIRE is a new topology optimization tool to explore on different application of weldment to casting conversion.

- ✓ Very less references for effective casting design & development from weldment designs are available and that too with conventional methods of optimization.

3 Methodology Proposals



Weldment to casting conversion + Topology Optimization using INSPIRE → FIRST TIME RIGHT CONCEPT DESIGN

Selecting an application & identifying suitable candidate

Evolve optimized material distribution as per constraints/targets

Right amount of material at right functional areas as per design/manufacturing/ assembly requirements

3.1 Objectives

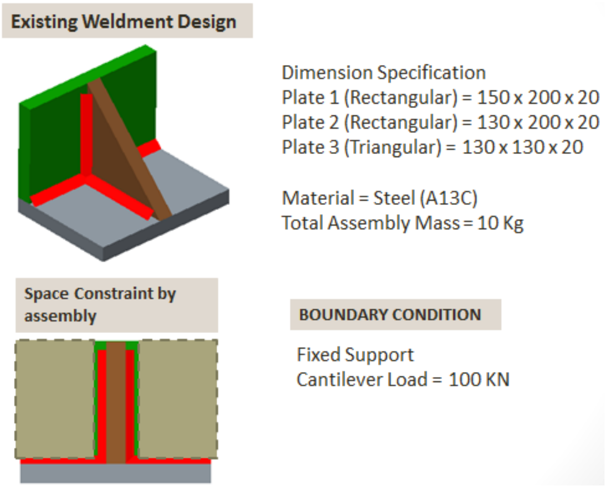
- ➢ To utilize the significance of topology and shape optimization techniques in product development cycle to save the number of iterations while modifying design by means of analysis inputs.
- ➢ To compare the design merits & demerits of casting and steel weldment for the same application and studying the stress distribution & deformation by static structural analysis.

3.2 Scope

- ➢ To develop the fundamental of a benchmark design (simple L-bracket with stiffener) that can be used by design engineers in comparing the structural advantages of castings and steel weldment under static load condition.

4 Implementation of Proposal –Case Studies

Fig 1: Detailed Problem Definition



Existing Weldment Design

Dimension Specification
Plate 1 (Rectangular) = 150 x 200 x 20
Plate 2 (Rectangular) = 130 x 200 x 20
Plate 3 (Triangular) = 130 x 130 x 20

Material = Steel (A13C)
Total Assembly Mass = 10 Kg

Space Constraint by assembly

BOUNDARY CONDITION

Fixed Support
Cantilever Load = 100 KN

Fig 2: Casting Design by conventional method

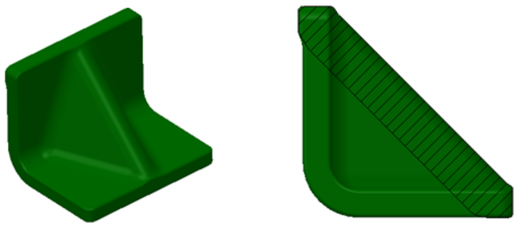
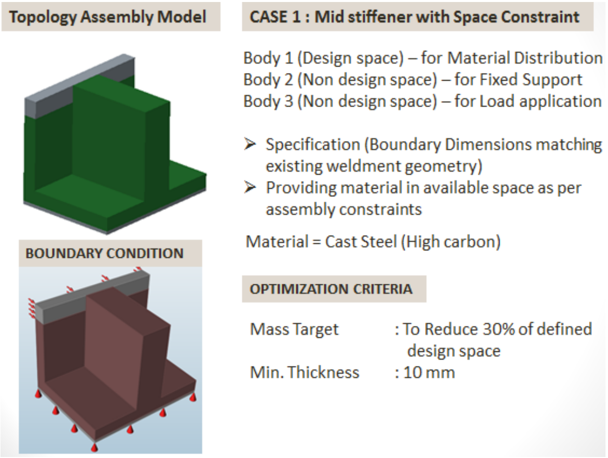


Fig 3: Case1: Topology Optimization Model Definition



Topology Assembly Model

CASE 1 : Mid stiffener with Space Constraint

Body 1 (Design space) – for Material Distribution
Body 2 (Non design space) – for Fixed Support
Body 3 (Non design space) – for Load application

- ➢ Specification (Boundary Dimensions matching existing weldment geometry)
- ➢ Providing material in available space as per assembly constraints

Material = Cast Steel (High carbon)

BOUNDARY CONDITION

OPTIMIZATION CRITERIA

Mass Target	: To Reduce 30% of defined design space
Min. Thickness	: 10 mm

Fig 4: Case1: Optimized Topology using INSPIRE

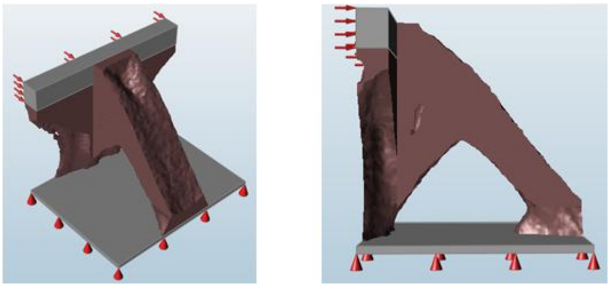


Fig 5: Case1: Redefined casting design by shape optimization

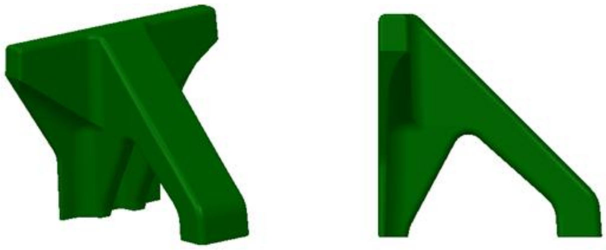
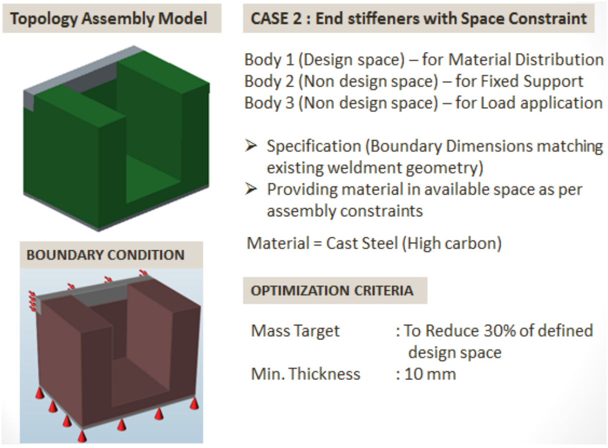


Fig 6: Case2: Topology Optimization Model Definition



Topology Assembly Model

CASE 2 : End stiffeners with Space Constraint

Body 1 (Design space) – for Material Distribution
Body 2 (Non design space) – for Fixed Support
Body 3 (Non design space) – for Load application

- Specification (Boundary Dimensions matching existing weldment geometry)
- Providing material in available space as per assembly constraints

Material = Cast Steel (High carbon)

BOUNDARY CONDITION

OPTIMIZATION CRITERIA

Mass Target : To Reduce 30% of defined design space
Min. Thickness : 10 mm

Fig 7: Case2: Optimized Topology using INSPIRE

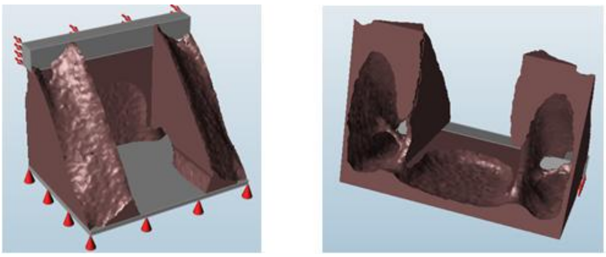


Fig 8: Case2: Redefined casting design by shape optimization

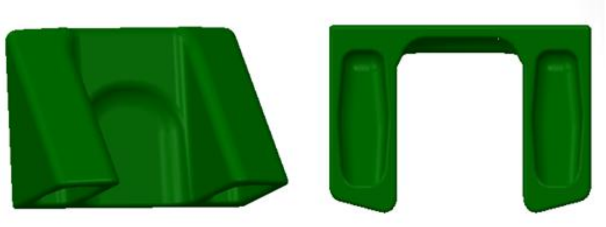
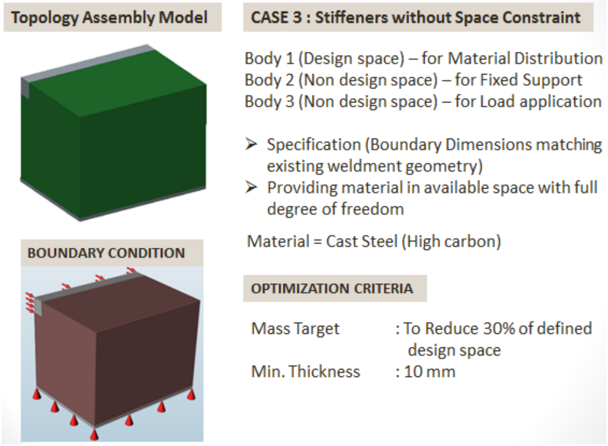


Fig 9: Case3: Topology Optimization Model Definition



Topology Assembly Model

CASE 3 : Stiffeners without Space Constraint

Body 1 (Design space) – for Material Distribution
Body 2 (Non design space) – for Fixed Support
Body 3 (Non design space) – for Load application

- Specification (Boundary Dimensions matching existing weldment geometry)
- Providing material in available space with full degree of freedom

Material = Cast Steel (High carbon)

BOUNDARY CONDITION

OPTIMIZATION CRITERIA

Mass Target : To Reduce 30% of defined design space
Min. Thickness : 10 mm

Fig 10: Case3: Optimized Topology using INSPIRE

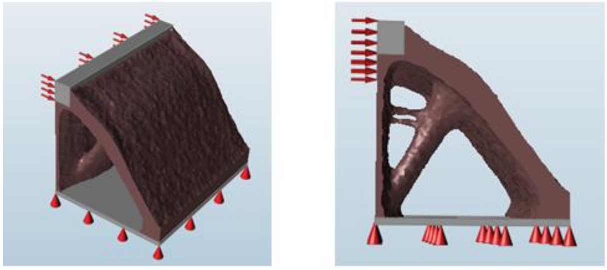
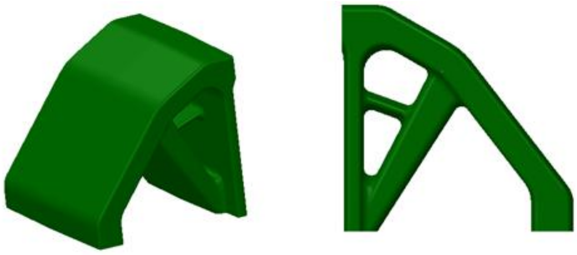


Fig 11:Case3: Redefined casting design by shape optimization



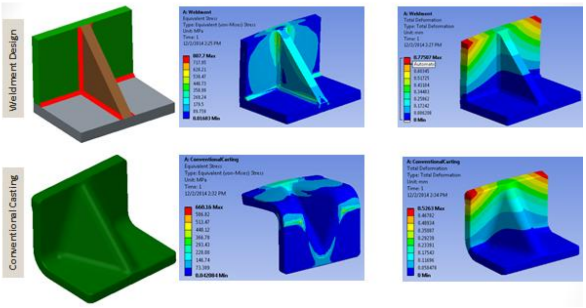
Other Possible Cases:

As per design strength requirements and manufacturing process constraints,theabove three cases can be further investigated

- With different casting material (such as Gray Iron, Ductile Iron, Aluminum, etc.)
- With different minimum thickness criteria

For the same boundary conditions

5 Static Structural Analysis of Weldment, Conventional and Casting designs



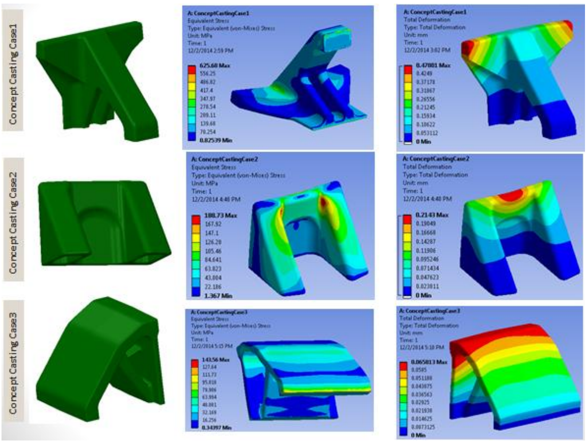


Fig12: Stress & Deformation plots

6 Selection of Concept Design

Objective Metrics /Concept Design	CASE 1 	CASE 2 	CASE 3 
Part Mass (in kg)	5.12	8.28	11
Max. Equivalent Stress (in Mpa)	350	188.7	143.6
Total Deformation (in mm)	0.478	0.214	0.066
Ease of Manufacturability	Manageable	Easy	Easy
Direct Material Cost compared to existing	Very low	low	At Par
Robust Design Solution	At Par (can be worked out)	Best	Best

Table1: Objective metrics of concept designs

7 Comparisons of Weldment, Conventional & Proposed Casting Designs

Design Type/ Parameters	Weldment Design	Conventional Casting Design	Casting Design using Topology Optimization
Component Mass (in Kg)	10	9.56	8.28/11
Number of Parts	3	1	1
Equivalent Stresses due to Applied Load Max.(in MPa)	807.7	365	188.7/143.6
Total Deformation (in mm)	0.776	0.526	0.214/0.066

Table2: Comparison of weldment, conventional & proposed designs

8 Research in realistic robust application

We arrived at twofrugal design proposals at the end of Project Stage I. When looking at the commercial and standardized design perspective, the evolved casting geometries are not appealing aesthetically from consumer/customer point of view. This point is taken after review with an industrial product engineer. So we relooked the problem definition and came up with a refined problem specification considering the customer voice/consumer satisfaction.

9 Refined Problem Definition

We have refined the design specification considering three benefits

- Realistic Application (bracket with bolt connection)for flexible design and service option
- Cost effectiveness (reduced thickness & optimized material thereby weight)
- Flexible material application

Also we got an opportunity to explore new technology for optimization resulting in

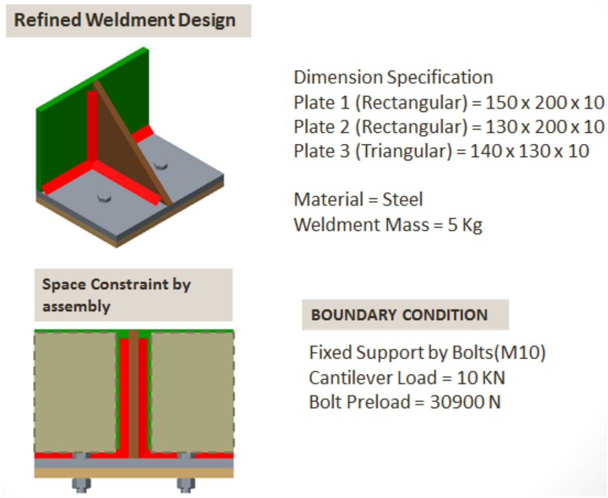
- Basic geometry preparation layout
- High confidence level with available possibilities
- Leveraged optimization tool behavior

Method of adopting new design specification in realistic application

- Model L-plate weldment (with stiffener) assembled with bolts
- Consider bolt load points for topology optimization
- Build/Refine casting models as per assembly constraints
  Design1: Reflecting topology geometry
  Design2: Geometry refined for ease of mfg. and less cost
- Finalize a standardized geometry
- Analyze weldment and optimized casting considering bolt preloads& applied load

10Implementation of Refined design

Fig 13: Detailed Refined Problem Definition



Refined Weldment Design

Dimension Specification
Plate 1 (Rectangular) = 150 x 200 x 10
Plate 2 (Rectangular) = 130 x 200 x 10
Plate 3 (Triangular) = 140 x 130 x 10

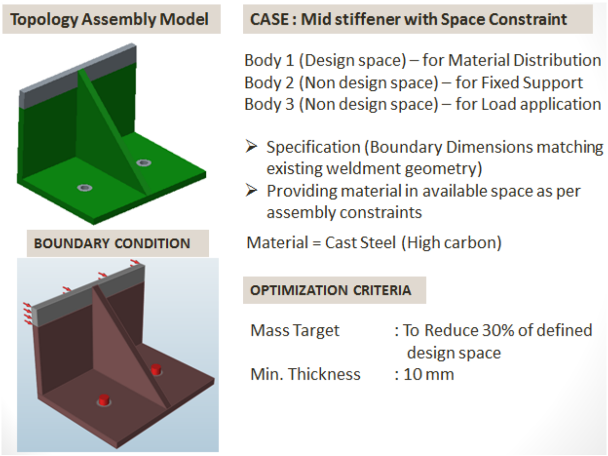
Material = Steel
Weldment Mass = 5 Kg

Space Constraint by assembly

BOUNDARY CONDITION

Fixed Support by Bolts(M10)
Cantilever Load = 10 KN
Bolt Preload = 30900 N

Fig 14: Topology Optimization Model Definition



Topology Assembly Model

CASE : Mid stiffener with Space Constraint

Body 1 (Design space) – for Material Distribution
Body 2 (Non design space) – for Fixed Support
Body 3 (Non design space) – for Load application

- Specification (Boundary Dimensions matching existing weldment geometry)
- Providing material in available space as per assembly constraints

Material = Cast Steel (High carbon)

BOUNDARY CONDITION

OPTIMIZATION CRITERIA

Mass Target : To Reduce 30% of defined design space
Min. Thickness : 10 mm

Fig 15: Optimized Topology using INSPIRE

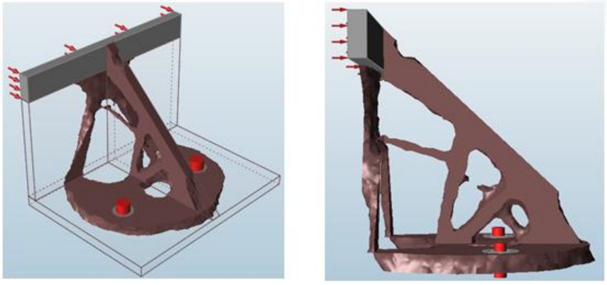


Fig 16: Design1: Refined casting design by shape optimizationreflecting topology geometry

Fig 17: Design2: Refined casting design by shape optimizationfor ease of manufacturing and less cost

11 Static Structural Analysis of Refined Weldment and Selected Casting Design

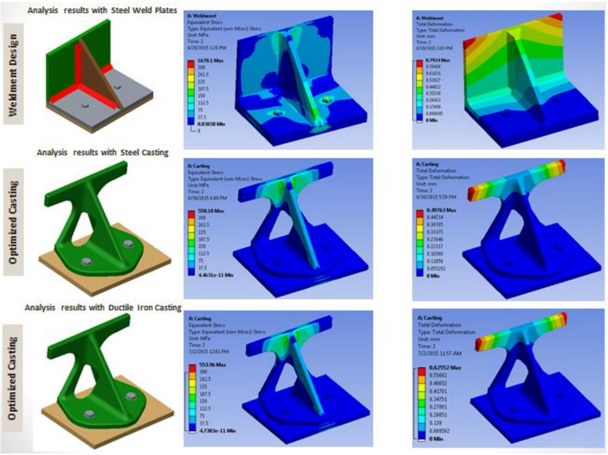
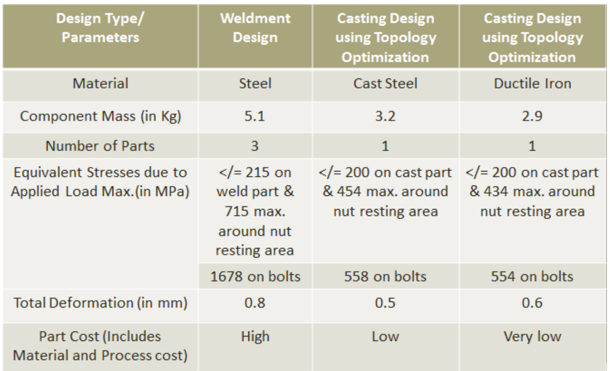


Fig18: Stress & Deformation plots

12Comparisons of Refined Weldment&Selected Casting Design



Design Type/ Parameters	Weldment Design	Casting Design using Topology Optimization	Casting Design using Topology Optimization
Material	Steel	Cast Steel	Ductile Iron
Component Mass (in Kg)	5.1	3.2	2.9
Number of Parts	3	1	1
Equivalent Stresses due to Applied Load Max.(in MPa)	</= 215 on weld part & 715 max. around nut resting area	</= 200 on cast part & 454 max. around nut resting area	</= 200 on cast part & 434 max. around nut resting area
	1678 on bolts	558 on bolts	554 on bolts
Total Deformation (in mm)	0.8	0.5	0.6
Part Cost (Includes Material and Process cost)	High	Low	Very low

Table3: Comparison of weldment &casting designs

Conclusions

Casting design performs better than weldment design in the case of benchmarked L-bracket with stiffener in bolted condition.The benefits of casting design compared to weldment design are as follows. (i) 37%-43% weight reduction (ii) Lower stresses which are less than 200 MPa on cast part comparatively (iii) Less deformation and (iv) Lower part cost.

As a development phase, both the weldment & casting part will be manufactured identifying the suitable suppliers and the assembled setup with bolts will be tested for stresses and deformation for the given static load condition in Universal Testing Machine.

Effectiveness of the topology optimization method is proved both by saving design time and product cost delivering robust concept design with desirable quality.

Designer gets best reference values for the structural benchmarked design between steel weldment and casting for the same application under static load conditions.

Future Scope: We can apply the procedure of optimization on the complex geometry of weldment design which includes large number of parts to convert to single casting design. This could result in huge savings of production cost. Also material for converted casting design can be enhanced as per functional requirement of the application thereby improving the life of the part.

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