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Superalloy Lattice Block

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November 2003

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Task Order #14 Final Report
May 15, 2003

Abstract:

Robust, lightweight component designs are critical to aircraft gas turbine engine performance, efficiency and application. Lightweight, superalloy lattice block structures composed of an open core with three-dimensional trusses have been examined as an alternative to bulk, fully dense, high-temperature static structures due to their strength, stiffness, and reduced weight. An assessment of the producibility and capability of these structures for aircraft gas turbine engine components suggests that the complexity of lattice block structure geometry may impose constraints upon the manufacturing method, design, and sizes of component structures produced. Preliminary analysis of an exhaust nozzle flap component indicates that weight reductions of up to about 30% may be achieved over conventional designs by integrating lattice block elements, but limitations in design analysis tools for these complex structures has prevented consideration of truss buckling in this analysis. Based on an application-focused assessment, recommendations are made regarding additional technical development needs envisioned before implementation of lattice block structures would be possible for aircraft gas turbine engine components.

1.0 Introduction:

Design and development of advanced aircraft gas turbine engines requires continued improvements in engine efficiency, engine and life cycle costs, component durability and reliability, and component capability. Improvements in materials and manufacturing processes are often critical to realizing overall improvements in efficiency and component capability. Reduced engine system weight also has a significant impact on the overall engine performance and has a subsequent impact on airframe weight and performance. Lightweight materials and structures are critical to reducing system weight and achieving target performance goals.

Various approaches have been pursued in order to develop lightweight components and assemblies [1]. Traditional lightweight structure designs often include the use of waffle patterns, honeycombs, hat-type stiffeners, and beams. Many of these techniques, such as honeycomb sandwich structures, are highly weight efficient, but require complicated fabrication and inspection methods, and result in structures with highly directional properties. As a result, many of these structures have achieved only limited application in the gas turbine engine primary static structure. Some traditional and advanced approaches to minimum weight designs are shown in Figure 1.1. In recent years, significant advances have been made in the use of composites and other advanced lightweight structures for various static structures and selected rotating parts. Improved structures have been developed, but continued pressure for reduced weight balanced with producibility and production cost effectiveness require that greater advances be made in developing alternate minimum weight materials and structures.

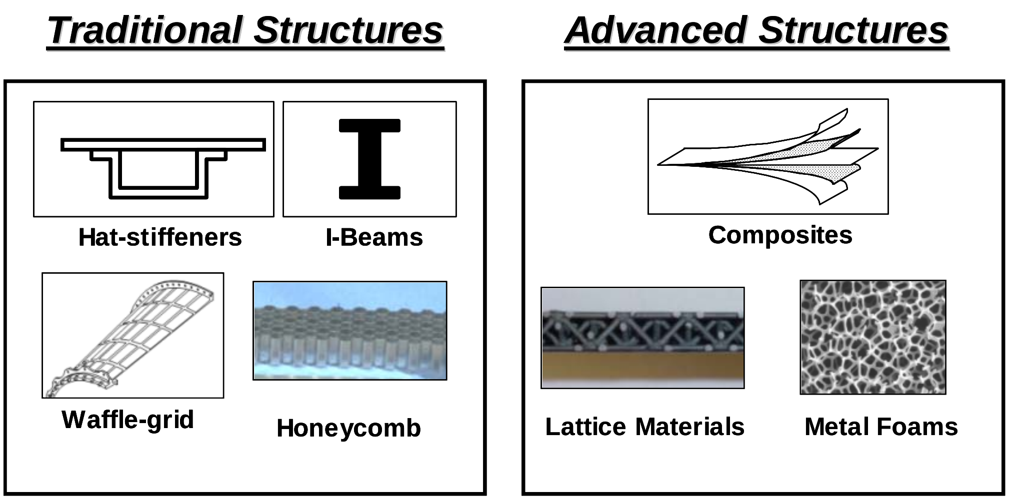


Figure 1.1: Some traditional and advanced approaches to minimum weight structures.

Approaches to lightweight design can vary significantly depending upon the temperature and strength capability requirements of a given component or assembly. At temperatures below about 200°F, aluminum alloys are effective, lightweight materials for low to moderate strength capability requirements and titanium offers additional strength and temperature benefit, but at a higher density. Material selection approaches to minimum weight design can also be effective for structures which operate up to approximately 1000°F by considering various conventional titanium alloy materials either in cast or wrought forms. At temperatures above 1000°F, strength and stability requirements limit material utilization to much higher density alloy systems, most typically superalloys based on nickel, cobalt, and/or iron. Lightweight design and manufacture of metallic components for high temperature service, as a result, have been limited significantly by high alloy material densities for superalloys. Alternate structure approaches are required in order to further reduce the weight of traditional superalloy structures.

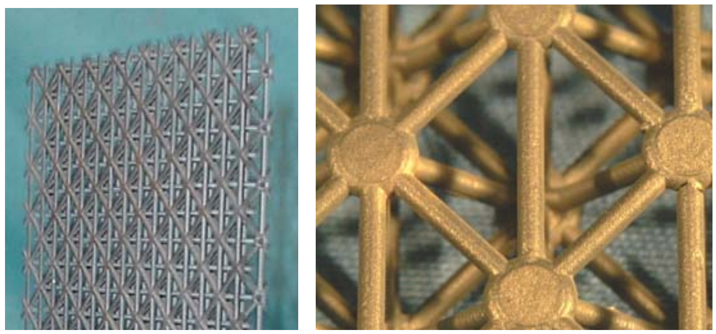


Figure 1.2: An example of a lightweight three-dimensional truss-type structure

A new class of lightweight metallic structures composed of three-dimensional arrangements of truss-type configurations have received recent attention [1-3]. An example of one such structure is shown in Figure 1.2. These material structures have been referred to as lattice materials and Lattice Block Material™ (LBM™) [4-7], truss core structures, 3D truss materials [8], truss structures [9], and more generally cellular materials [7]. This study will use the terminology Lattice Block (LB) structure.

Example LB structure geometries are shown schematically in Figure 1.3. These structures consist of ligaments which form the trusses of the structure. Several ligaments come together at nodes, and the ligaments and nodes are arranged in a repeating geometry. Each repeated truss arrangement is referred to as a unit cell. Many unit cells are then used to make a structure.

This LB structure [2-3] provides an alternate design solution to development of light weight, high stiffness components using a unique three-dimensional truss structure formed by investment casting, sheet fabrication, or deposition buildup methodologies. This structure provides significant improvements in shear strength compared to honeycomb structures. Panels of such structures have been manufactured from aluminum and steel, as well as from other non-metallic materials [2,4,8]. Initial work has also been performed examining LB structures composed of high-temperature, nickel-based superalloy materials such as Alloy 718 and MarM247 [4-6]. Potential gas turbine applications of these lightweight designs have been previously indicated [4] including exhaust nozzle actuated panels, flaps, and side panels; however, most studies have examined LB behavior from a more general, experimental and analytic approach. An application-focused assessment effort has been largely lacking in evaluation of these lattice structure geometries.

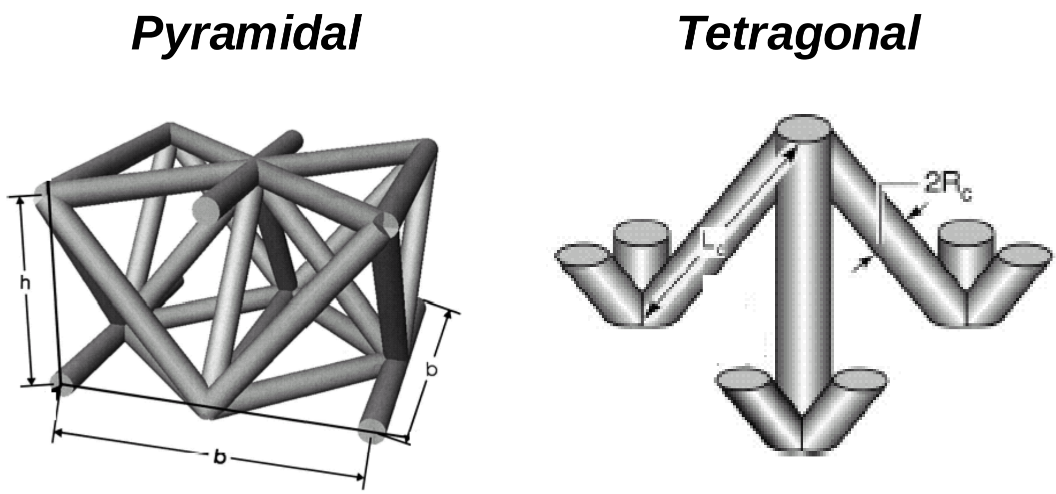


Figure 1.3: Lattice block structure optimized truss arrangements (unit cells) illustrating ligaments and nodes formed by the intersection of ligaments as described by Wallach and Gibson [10] and Chiras, *et al.*[11].

Several studies have examined construction [3], mechanical behavior [2,6-8,10], and structure optimization [1,9] under relatively simple loading conditions primarily for flat panel configurations. Typical three-dimensional structures examined to date include those with square, diamond, tetragonal, pyramidal, and octahedral truss configurations. Tetragonal and pyramidal LB structure arrangements have been reproduced [10,11] in Figure 1.3 for reference and ease in understanding. Other more complicated structures including Kagomé truss configurations have also been discussed in the literature [1]. Designs may impose a variety of loading conditions on the structure and may also utilize some dual-use advantages of these structures as summarized in Figure 1.4. The design, manufacture, analysis, and mechanical performance of these three-dimensional truss-type structures is not yet mature; however, progress has been made in better understanding these configurations and their performance. Many structure parameters must be considered in optimizing the base lattice geometry for a particular application and a partial list of relevant parameters for consideration in structure optimization is shown in Figure 1.5. This study examines potential component applications, constraints, and demonstration opportunities for continued development and implementation of LB technology in aircraft gas turbine engines.

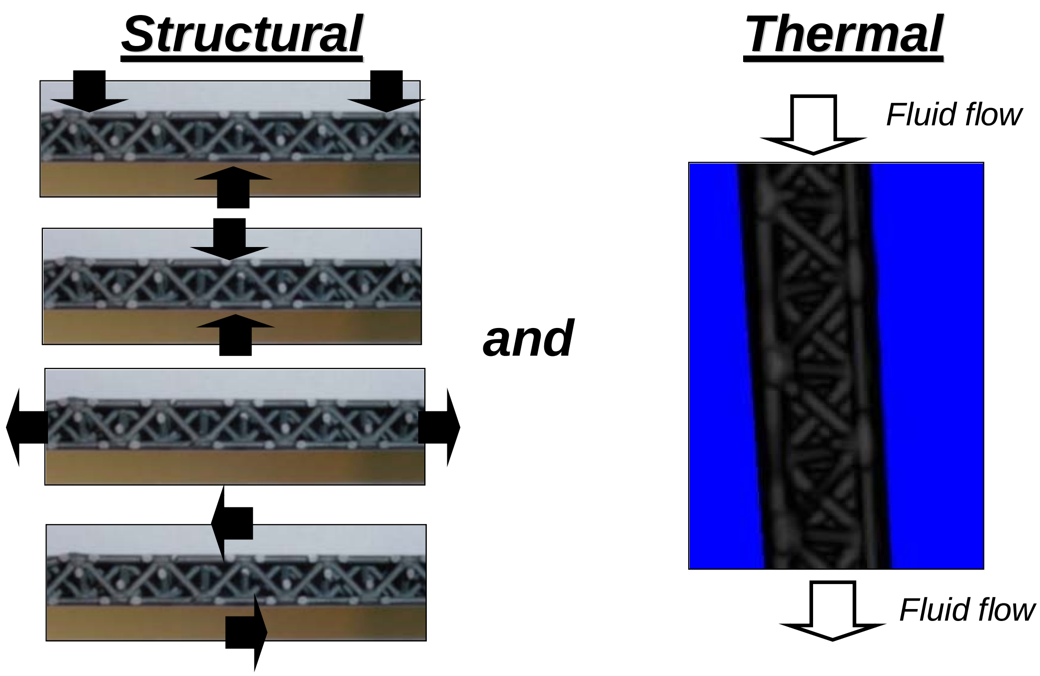


Figure 1.4: Summary of various possible loading conditions and a potential dual use aspect of the lattice block structure.

Lattice Blocks

- ***Ligament***
  - ***geometry***
    - ***aspect ratio***
    - ***cross section***
    - ***diameter***
- ***Node***
  - ***intersection point vs. faces***
  - ***degree of constraint***
  - ***design***
- ***Structure***
  - ***number of stacked elements***
  - ***face sheet vs. open cell face***
- ***Material***
  - ***strain at yield, ultimate***
  - ***modulus***
  - ***tension/compression asymmetry***

Figure 1.5: A partial list of the parameters requiring assessment in order to optimize a given lattice structure.

2.0 Approach

The specific objective of this study is to evaluate the potential of superalloy LB's for advanced aircraft gas turbine engine component applications. Specific objectives are:

(1) Identify suitable engine components
(2) Define property goals for successful application
(3) Project quantitative benefits
(4) Identify a rough order of magnitude plan, tasks, technology, and costs leading to a demonstration test.

The primary focus targets supersonic engine applications including advanced military and commercial engines, but considers subsonic applications as well. The effort was organized into 4 tasks which are detailed in this section. A complete schedule is given in Figure 2.1. During performance of the study, limitations in the development of complex structures and predictive capability for such structures resulted in some limitation as to the quantification of specific requirements and benefits and also curtailed the detail to which a demonstration plan could be formulated. Where data and analysis techniques were not available, engineering judgment and explicitly indicated assumptions were used to provide a best estimate within the analysis constraints.

Task 1: Candidate Component Identification:

Identification of candidate aircraft engine components which may be able to take advantage of the weight and structural benefits of the LB structure includes several sub tasks involving application scoping, assessment of structural capability and producibility, and selection of engine-specific components which fall within the application scope and capability assessment. Initial scoping of application types involved determination of families of parts with benefit potential. Assessment of capability included estimation of mechanical performance of this structure and the practical casting producibility constraints which bound component size, structure, geometry, section thickness, and ligament aspect ratio. This initial assessment was made based on published literature data, NASA testing results, and conventional manufacturing practice experience. This assessment forms the basis for selection of engine-specific components in this task. Engine components were selected by a multidisciplinary Team including Material and Design Engineers. Selected components were then further analyzed in subsequent tasks. In order to focus on components which have a balance of high perceived benefit and low to moderate implementation risk, the field of potential applications was narrowed at the end of Task 1.

Task 2: Determination of Material and Process Requirements:

A more detailed assessment of key requirements was performed once candidate applications, which fell within the bounds of anticipated structural capability and producibility, were identified. This task focused on specifying the mechanical capability required for specific applications, overall geometric producibility requirements, and quality requirements which must be met for successful application of LB structures.

Task 3: Benefit Quantification:

The LB structure presents obvious benefits including reduced weight over equivalent sized solid structures, and improved stiffness over equivalent weight solid structures. Additional benefits may also be realized. For a selected component, a more comprehensive list of benefits was identified based on LB's. Estimation of the magnitude of application benefits was performed to better rank application potential. This assessment also involved a multidisciplinary Team of Materials and Design personnel.

Task 4: Rough Order of Magnitude Component Demonstration Plan and Report:

The candidate component applications were assessed for demonstration test opportunities. Selection and recommendation of a specific component or components for design, prototype manufacture, and testing were to be driven by anticipated benefits, component criticality/risk, near term producibility, and engine/test rig availability and timing. Technical issues and needs were also briefly addressed in order to establish the required technical scope for additional efforts to implement LB's. Due to limited funding resources on this program and delays resulting from difficulties on the benefit analysis, activities in this task were discontinued prior to their completion with the approval of NASA.

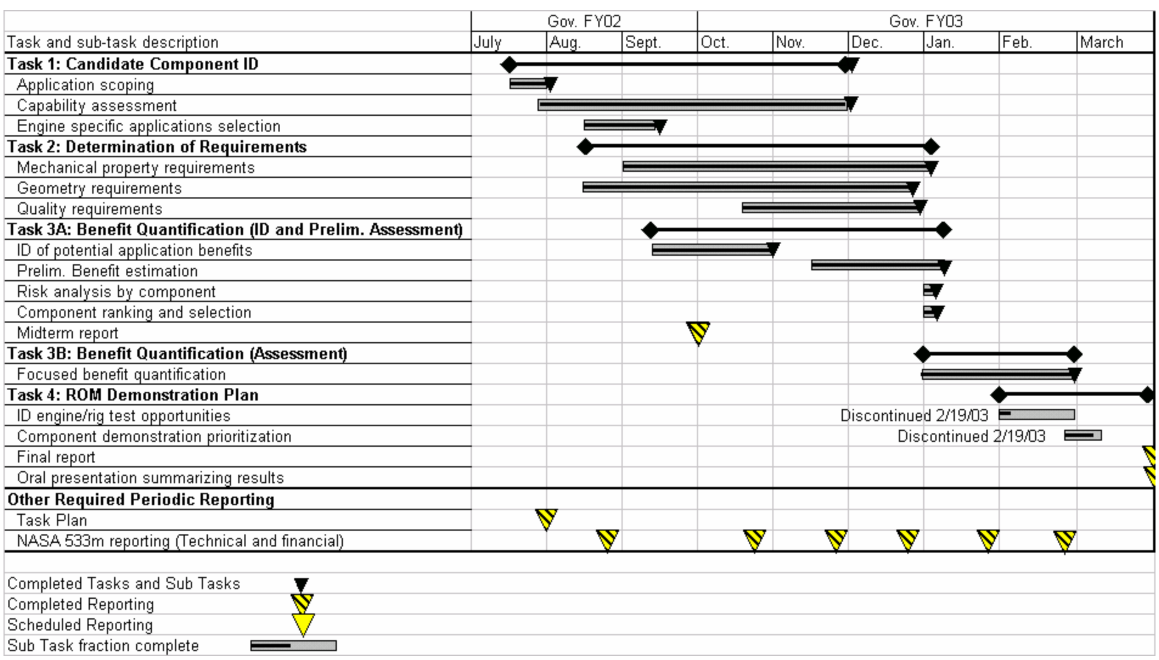


Figure 2.1: Overall Schedule and Task summary for the present study.

3.0 Candidate Component Identification:

Efforts to identify and select candidate components for more detailed assessment were performed by first establishing component application types and candidate engine applications. For the identified application scope, an assessment of producibility and an analysis of structural capability was performed based on literature and other application experience. Potential applications were then rationalized in terms of complexity and implementation risk. Components and applications with an acceptable balance of risk and expected engine system impact were then selected for additional consideration.

3.1 Application Scoping:

A thorough discussion of potential advanced components and engine system applications involved Materials and Design engineers for production and development engineering areas. As a result, the application scope was narrowed to the following component types for consideration: cases, shrouds, frame struts and liners, exhaust system components and actuator and control hardware. The primary engine system focus was directed toward advanced commercial and military engines including the Quiet Supersonic Platform (QSP) and Revolutionary Turbine Accelerator (RTA). Nearer term production applications were also considered.

3.2 Manufacturing Producibility:

Gas turbine engine components produced using conventional design approaches and material structures are typically manufactured using investment casting processes, wrought processing (including forging, ring rolling, and forming of sheet, and plate) and subsequent machining, or fabrication processes using one or more of these product forms. The critical nature of aircraft engine applications, component weight limitations, and cost constraints dictate that production manufacturing processes must produce robust, reliable, components at an acceptable quality level, cost, and weight. In order to insure quality and promote manufacturing process robustness, component designs must be matched to production processes with sufficient capability to meet geometry, quality, and dimensional requirements. Effective component inspection is also important to continual monitoring of quality. As a result, producibility and inspectability have been closely examined in this assessment of LB structures for turbine applications. Practical geometry limitations based upon conventional manufacturing process technology will be considered, specifically for purposes of guiding establishment of candidate components most likely to meet requirements and be ultimately producible.

In previous studies, test panel geometries of the LB structure have been produced through several manufacturing techniques including casting, sheet fabrication, and deposition buildup. Examples of investment cast LB structures provided by NASA for evaluation during this study can be found in Figure 3.1. These structures may have solid faces or open cell faces as shown in the example. Investment casting and fabrication processes are widely used in the industry and will be the primary focus of the analysis in this assessment. Deposition buildup processes including laser additive manufacturing [12] and other direct rapid prototyping processes have been used to manufacture complex structures, but these technologies are, at this time, not in widespread use as production manufacturing processes and, as a result, were not considered in detail.

Figure 3.1: Typical views of Jamcorp™, Inc. Ni-based LB test panels showing the complex 3 dimensional truss structure and the ability to cast open structures or panels with face sheets.

3.2.1 Casting Producibility

LB casting producibility was examined relative to three major areas of concern: feature producibility, wall thickness/size constraints, and geometric tolerance capability. As a result, rough guidelines were established for selection of potential components using the LB structure. Two manufacturing methods, investment casting and fabrication from wrought sheet products, will be considered in this assessment.

Investment castings for turbine engine component applications are typically complex in geometry. The complexity is driven by the structural and aerodynamic requirements of the component, the desire for minimization of post-casting machining operations, and the ability to reliably manufacture desired features in a production atmosphere. In addition to the overall component size and geometry, other cast features are also critical to component manufacture. Typical features of interest in investment cast components include: bolting flanges, integral airfoil-shapes, attachment bosses and pads, and passages for various component feed-throughs. The producibility of these features in conjunction with the LB structure has not been previously examined in detail for Ni-based casting alloys, although concepts integrating some similar features have been envisioned [2].

Assessment of structure producibility for investment cast LB structures was performed based on industry experience in cast components and published literature [13-15] on casting processes and process improvement efforts. The most significant constraints regarding producibility relates to those imposed by conventional investment casting processes on the ability to produce large, thin walled structures. Figure 3.2 gives an estimate of the practical ligament and face sheet thickness capability as a function of the structure size for typical nickel casting processes. Specific configurations can depart from this estimate depending upon alloy, casting geometry, component features, and casting and gating processes, but this represents normally achievable section thickness lower bounds for casting producibility.

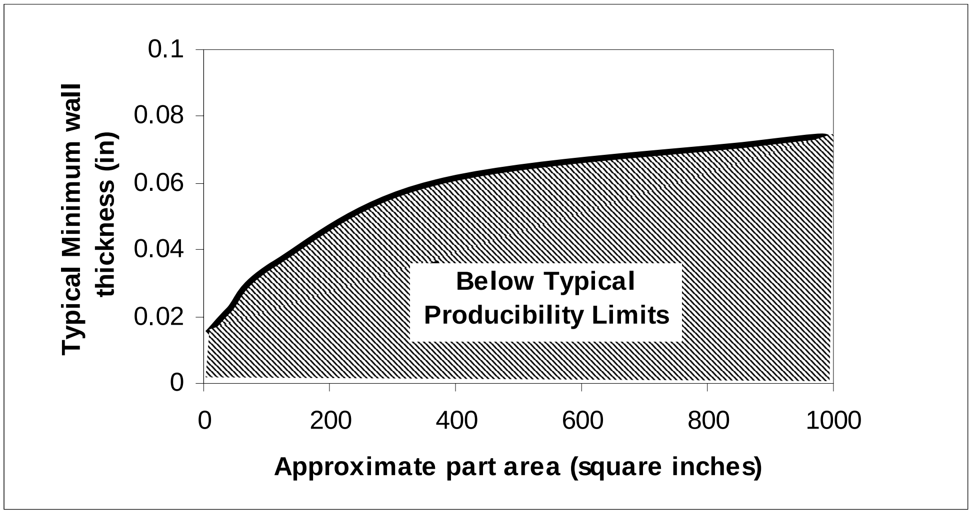


Figure 3.2: Estimate of the normal capability bounds for minimum section thickness in investment cast nickel-base alloys as a function of component size.

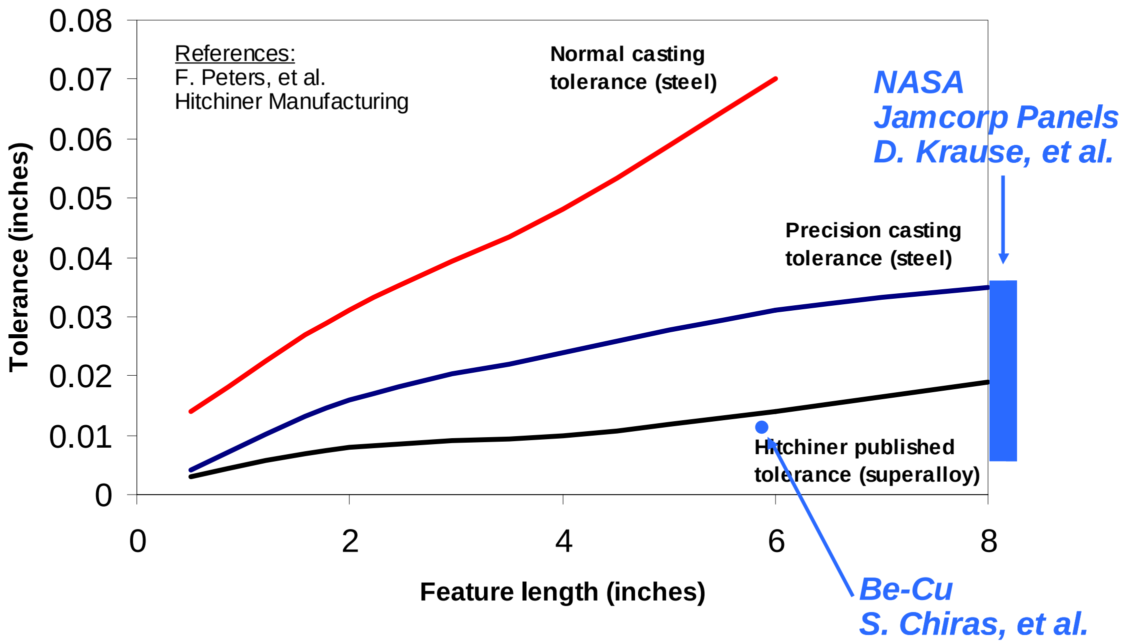
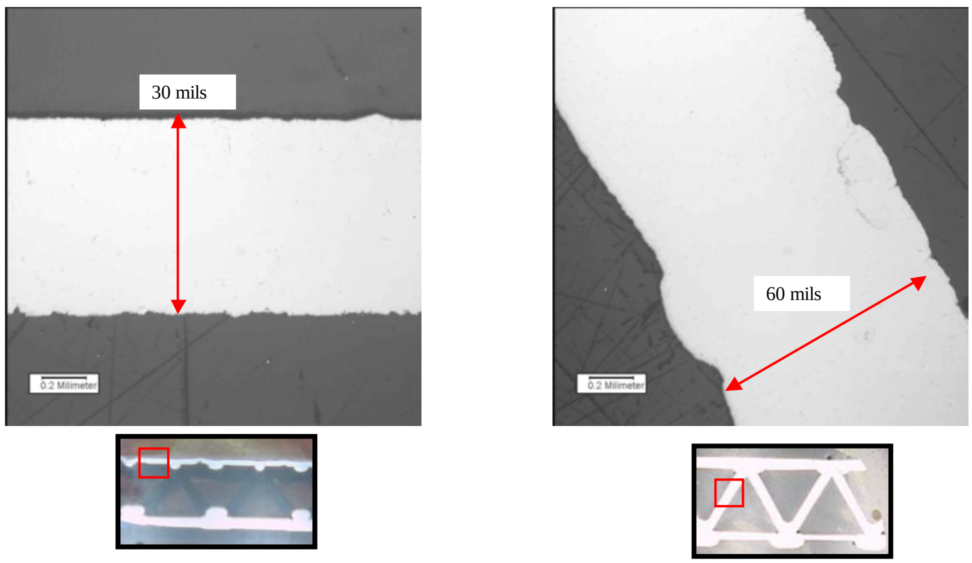


Figure 3.3: Typical casting dimensional tolerance capability [16,17] and comparison to specific lattice structure cast panels reported by Krause [4] and Chiras [11].

Potential LB components, particularly those which would replace components fabricated from sheet material, beams, and stringers will likely require designs with ligament thicknesses of 0.080” and thinner for lattice ligaments and face sheets in order to take advantage of the weight efficiency of these structures relative to conventional component designs. As a result, the maximum overall size of the LB component may be limited by typical maximum part sizes which can be produced at section thicknesses of below 0.080”. These overall size constraints may be relaxed by considering component designs which are composed of smaller, integrally cast LB segments separated by slightly thicker walled, more conventionally designed regions. The addition of thicker wall sections adjacent to thin walled LB structure regions within a single casting can act to enhance feeding of the thin wall sections, thus improving producibility. Similar benefits may also be possible when considering various integrally cast attachments including bolting flanges, attachment bosses and pads, and feed-through structures. Design of the component geometry transitions between LB thin walled regions and thicker walled regions should follow standard guidelines for casting geometry optimization for producibility similar to that summarized briefly by Bidwell [18] and others [16].



Face Sheets ***Core Ligaments***

Panels courtesy of NASA-GRC

Figure 3.4: Typical cross sections of Jamcorp, Inc. Lattice Block Material, Alloy 718 and MarM247, with and without a continuous face sheet, provided as part of this study.

An assessment of typical geometric tolerances is also necessary in order to understand both the producibility of large thin walled castings and thin walled regions of larger castings which incorporate both thin and thick wall sections. Assessment is also critical in determining anticipated production tolerances for LB’s which incorporate thin ligament section sizes. Typical dimensional tolerances for various steel and nickel investment castings [16-17] can be used to better understand producibility of LB structures. A summary is shown in Figure 3.3. Assessments by Peters, *et al.* [17], and published by Hitchiner Manufacturing, suggests that ligament diameter tolerances of less than 0.004” are likely possible for ligament diameters of approximately 0.060”. Similarly lattice structure unit cell spacing tolerances of 0.010” or less are likely possible for unit cell spacings of 0.25”. Overall length tolerance for large sections of LB structure would be expected to be approximately 0.004” per inch of feature length. The inherent dimensional variability must also be considered when performing design analysis and capability assessment of the LB structure.

Table 3.1: Potential defect types in cast superalloy LB structures (note numbers correspond to Figure 3.5 photographs).

Defect Type	Typical location	Likely contributing causes
(1) Missing ligament sections	LB center	Inadequate feeding and fill
(2) Residual cast metal	Within ligament structure interstices	Local mold failure and leakage
(3) Face sheet cracking	Face sheet surfaces between and adjacent to trusses	Inadequate feeding of thin sections, hot tears during casting
(4) Ligament cracking	Any ligament segment orientation	Porosity, hot tears during casting, residual stresses, thermal stresses during cooling
(5) Partial fill in face sheets	Face sheet regions between trusses	Inadequate feeding and fill
(6) Porosity	Ligament segments and LB structure nodes	Inadequate feeding, surface connectivity of casting porosity, inadequate HIP conditions
(7) Metal-mold interaction	Casting surfaces adjacent to mold	Mold material, pour temperature, mold preheat, casting cooling rate
(8) Partial fill of truss ligaments	Ligaments particularly those integral to face sheets	Inadequate fill and feeding, low pour temperatures
Low density inclusions	Any cast sections	Mold failure, melt contamination
Segregation	Any cast sections	Casting conditions, alloy, section size, cooling rate, post casting processing

In order to characterize a typical cast LB panel, simple destructive evaluation and assessment of cast Alloy 718 and MarM-247 panels provided by NASA as part of this study was performed. Selected metallographic cross sections are given in Figure 3.4. Cast section size and overall panel size compare well to casting producibility restrictions given in Figure 3.2.

In addition, visual, macroscopic and microscopic metallurgical evaluation was performed on Alloy 718 and MarM247 LB panels in order to identify potential defects which may result from the casting process and may lead to property and/or reliability debits in the structure. Destructive evaluation of panel segments provided by NASA as part of this study was also performed on a limited basis. Potential defect types were identified based on this analysis and a knowledge of typical nickel-based alloy casting defects. Potential defects are summarized in Table 3.1 along with several potential causes. Typical examples of many of these casting-related defect types are also pictured in Figure 3.5. This list of potential defects and causes should not be considered an exhaustive list. This list, however, represents the most likely defect types based on limited LB examination and based on defect types reported previously for similar structures [4].

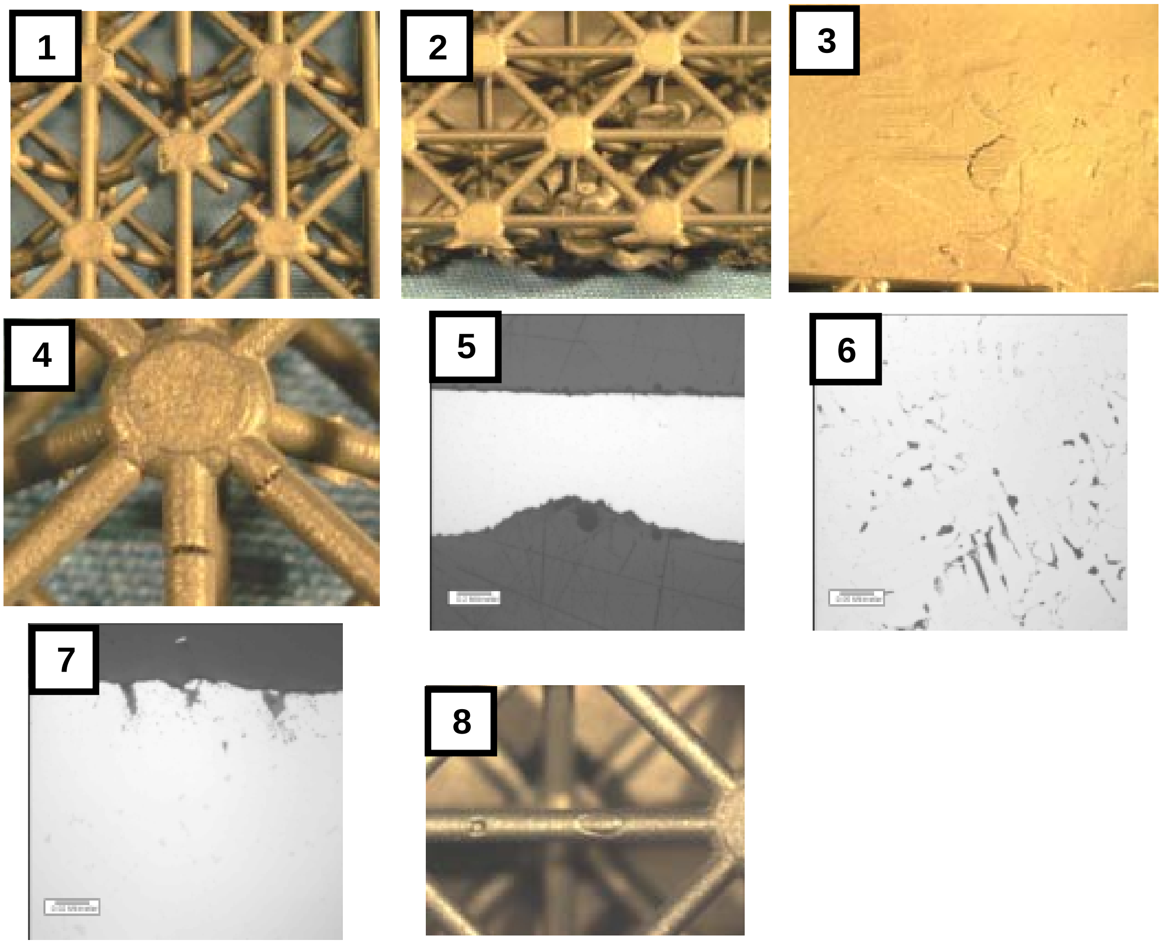


Figure 3.5: Example LB defects which may define structural capability and producibility limitations. Note that numbers correspond to identifications in Table 3.1.

3.2.2 Fabrication Producibility and Tradeoffs:

An additional approach which may relax some of the limitations imposed by casting has been indicated in previous publications on the subject [3]. Due to the geometry of various LB structures including the tetragonal and pyramidal core ligament configurations, the internal framework of the LB can be manufactured from sheet material. In such a fabrication, two face sheets would be joined to a third sheet that forms the three-dimensional internal ligament structure. This internal ligament structure may be manufactured from a flat sheet by cutting a repeating, closely spaced network of hexagonal, square, or diamond-shaped holes into the sheet followed by corrugation to form the appropriate three-dimensional structure. The ligament thickness is then a determined by the sheet thickness and the spacing of the closely-spaced hole pattern. This and other alternate fabrication technologies are shown pictorially in Figure 3.6 along with relevant constraints on wall thickness.

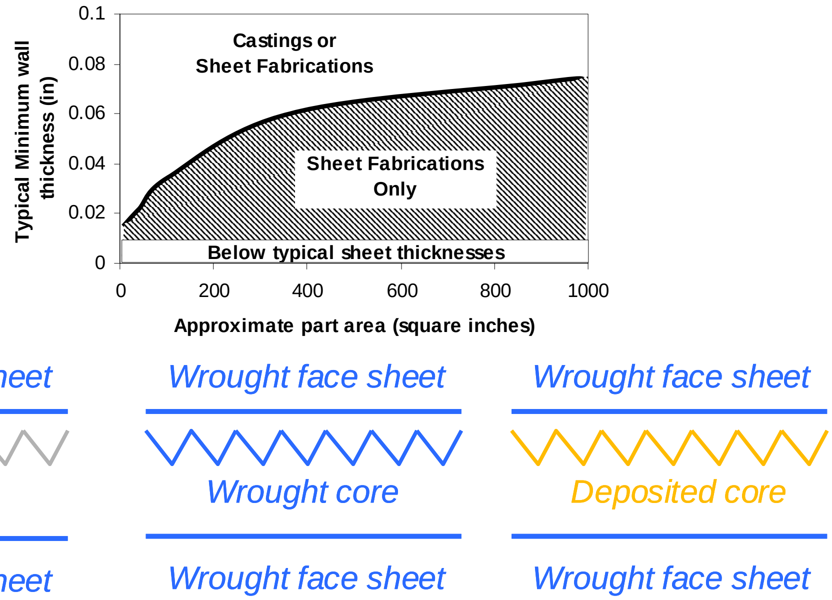


Figure 3.6: Alternate fabrication technologies to manufacture Lattice Block Structures and an estimate of the normal capability bounds for minimum wall thickness in nickel-based high temperature alloys as a function of component size.

Consideration of wrought LB structures via sheet fabrication results in significantly less section thickness constraint for large sized components. Sheet wall thickness constraints as well as those imposed by typical investment casting processes are summarized in Figure 3.6. . With finer ligament and face sheet thicknesses, the lattice ligament lengths and spacings must be reduced in order to reduce the propensity for buckling of individual ligaments when the structure is under load; however, reduced structure weights over that producible by investment casting may be possible under appropriate loading conditions.

Because this alternate approach relies upon significant fabrication operations including sheet forming, machining, corrugating, and joining (brazing and/or welding), production costs may be higher than that for a casting with a similar geometry. There are, however, several aspects that may result in additional benefit to structural capability, producibility, and utilization of alloys which are not easily castable in thin sections.

Table 3.2: Possible design and manufacturing considerations in evaluating casting or fabrication methods for producing LB structures.

Design/Manufacturing Element	Cast LBM	Fabricated LBM	Some related trade study elements
Fatigue strength	Lower	Higher	Weight, producibility, cost
Complex structure producibility	Higher	Lower	Weight, structural capability requirements
Cost	Trade required	Trade required	Weight, geometry, ligament thickness,
Likelihood of ligament defects	Higher	Lower	Structural capability requirements, structure damage tolerance, weight
Inspectability	Lower	Higher	Structural capability requirements, structure damage tolerance, weight, cost
Minimum ligament thickness bounds	Higher	Lower	Geometry, producibility, cost, weight
Alloy flexibility	Castable alloys	Wrought and powder alloys	Cost, weight, structural capability requirements
Minimum face sheet thickness	Higher	Lower	Structural capability requirements, weight, cost
Inclusion of integral bosses and flanges	Cast near net shape	Fabrication required	Cost, geometry
Choice in truss structure orientation in component	Flexible for complex components	Limited flexibility except in simple geometries	Structural capability requirements, weight

Table 3.2 summarizes some of the important considerations when evaluating the use of cast LB's and fabricated wrought LB's. Clearly, component geometries which fall within the bounds of casting capability, use conventionally castable alloys and have complex geometries, are more likely to be candidates for cast LB's. Structures with more simple geometries, fine ligament thicknesses, limited defect tolerance, and structural requirements which can only be met with wrought or powder metallurgy alloys, would be the more likely candidate for sheet fabrication methodologies. The manufacturing method choice would need to be driven by a detailed trade study between elements in Table 3.2 as applied to the candidate component geometry and requirements.

As an example, component temperature capability and strength requirements for a relatively simple panel-shaped component may necessitate that an oxide dispersion strengthened (ODS) nickel or iron based alloy be considered. Because these materials are typically only available as powder metallurgy products that subsequently receive thermo-mechanical working to produce product forms such as sheet and plate, casting is not possible. A fabricated LB structure would likely be the leading candidate manufacturing route.

3.2.3 Inspectability

Regardless of the LB manufacturing process path, component inspection is critical to monitoring process control and robustness, and in some cases, to identifying defects which can be reworked during manufacturing or repair processes. Limited LB non-destructive inspection work has been reported, and this limited published information involved characterization of test panels during investment casting process development [4]. Due to limitations in available test samples, an investigation of several investment cast LB materials provided by NASA as part of this study was performed to better understand inspectability of these complex structures. Similar concepts can also be generally applied to wrought components as well.

The presence of casting defects, their type, size, and location impose limitations on the structural capability of conventional castings. For LB structures, the three-dimensional layered structure, the ligament thickness, and the potential use of one or more face sheets integral to the structure surface impose significant complexities in inspecting and identifying casting-related defects. To date, inspection techniques used have been primarily visual whereas typical structural casting inspection in the aerospace industry includes a combination of one of more techniques including visual, fluorescent dye penetrant (FPI), radiographic, and ultrasonic. The level of inspection required is related to material, geometry, component function, design margin, and consequences of potential failure modes. Materials property data for component design and lifing of casting reflects potential defect types and their effect on properties for defects which are at or below the inspectability limit. The LB structure is significantly different from other conventional cast structures and additional differences and complications were anticipated in non-destructive evaluation of this and similar cast configurations. The defect types indicated in Table 3.1 were considered and ultrasonic and radiographic inspections techniques were used to understand which defect types could be reliably identified by non-destructive means. This analysis was limited to known defects that were present in LB panels which could be examined in this study.

Inspection was performed using high resolution ultrasonic (UT) scanning at 1 to 10MHz frequencies using either conventional UT equipment or a Phased Array UT system (GE Medical 4D system) or by digital x-ray radiography by Industrial Computed Tomography (ICT) techniques. UT testing is limited to material regions that are amenable to contact by the UT probe. As a result, UT scans were only useful in showing face sheet and integral ligament segment sections or surface LB nodes and ligaments. ICT scans permitted generation of three dimensional x-ray maps of the structure with a spatial resolution of approximately 0.030”. Digital ICT files were further manipulated on a Silicon Graphics workstation to locate specific areas with known defects and determine if the defects could be identified with similar techniques.

Typical UT inspection results from a MarM247 LB panel with an integrally cast face sheet are shown in Figure 3.7. Scans are two-dimensional projections of the face sheet and attached ligaments only or surface LB nodes. Results suggest that limited defect detectability can be achieved at 1MHz using conventional techniques. Phased array techniques enable reliable detection of missing ligaments and incomplete filling of ligament sections. Neither UT technique can be used to identify ligament cracks.

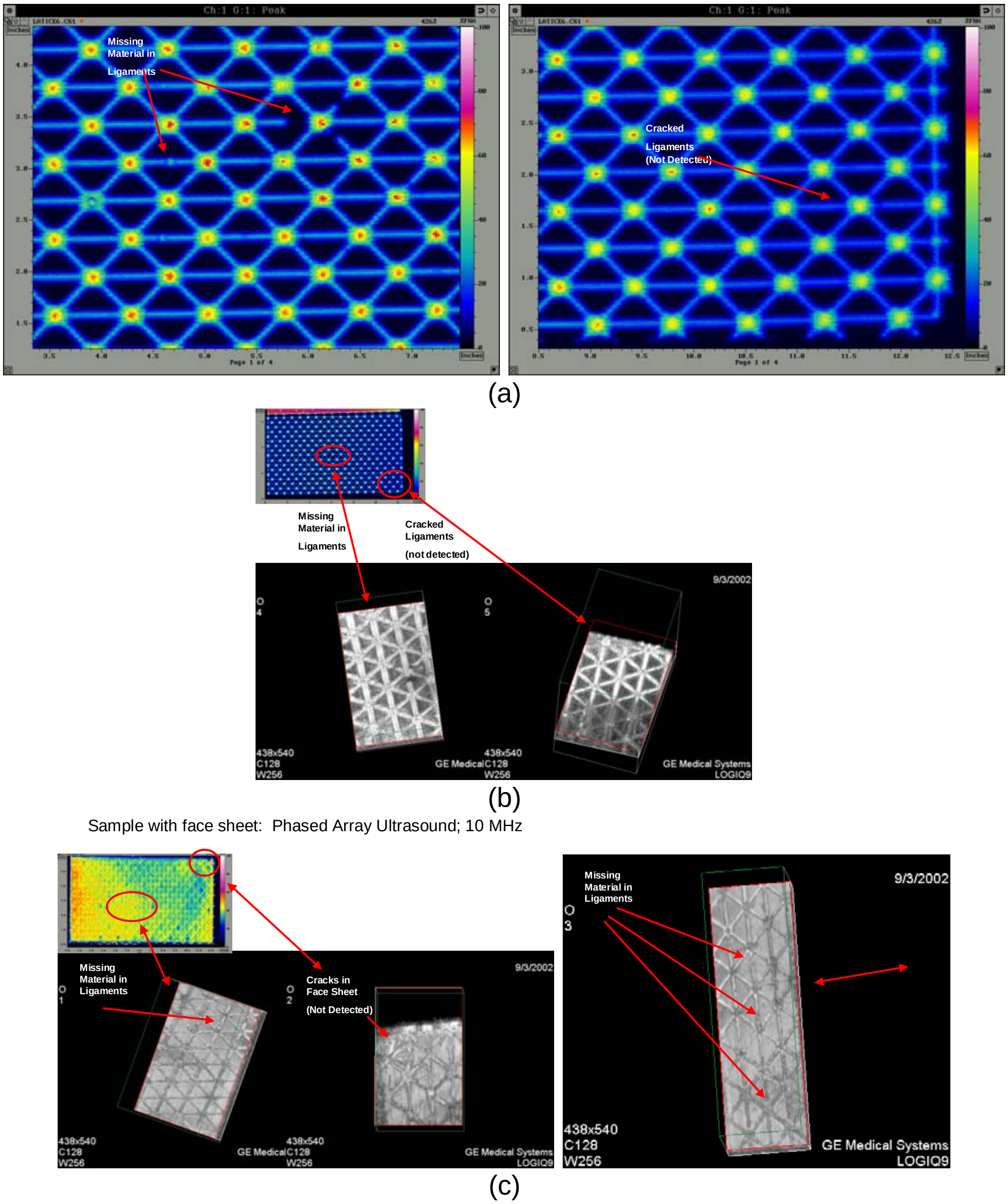


Figure 3.7: Ultrasonic inspection results from (a) Alloy 718 LB with no face sheet inspected with conventional UT at 1 MHz, and (b) with phased array UT at 10MHz, and results from (c) a MarM247 LB panel with a single face sheet using phased array UT at 10MHz.

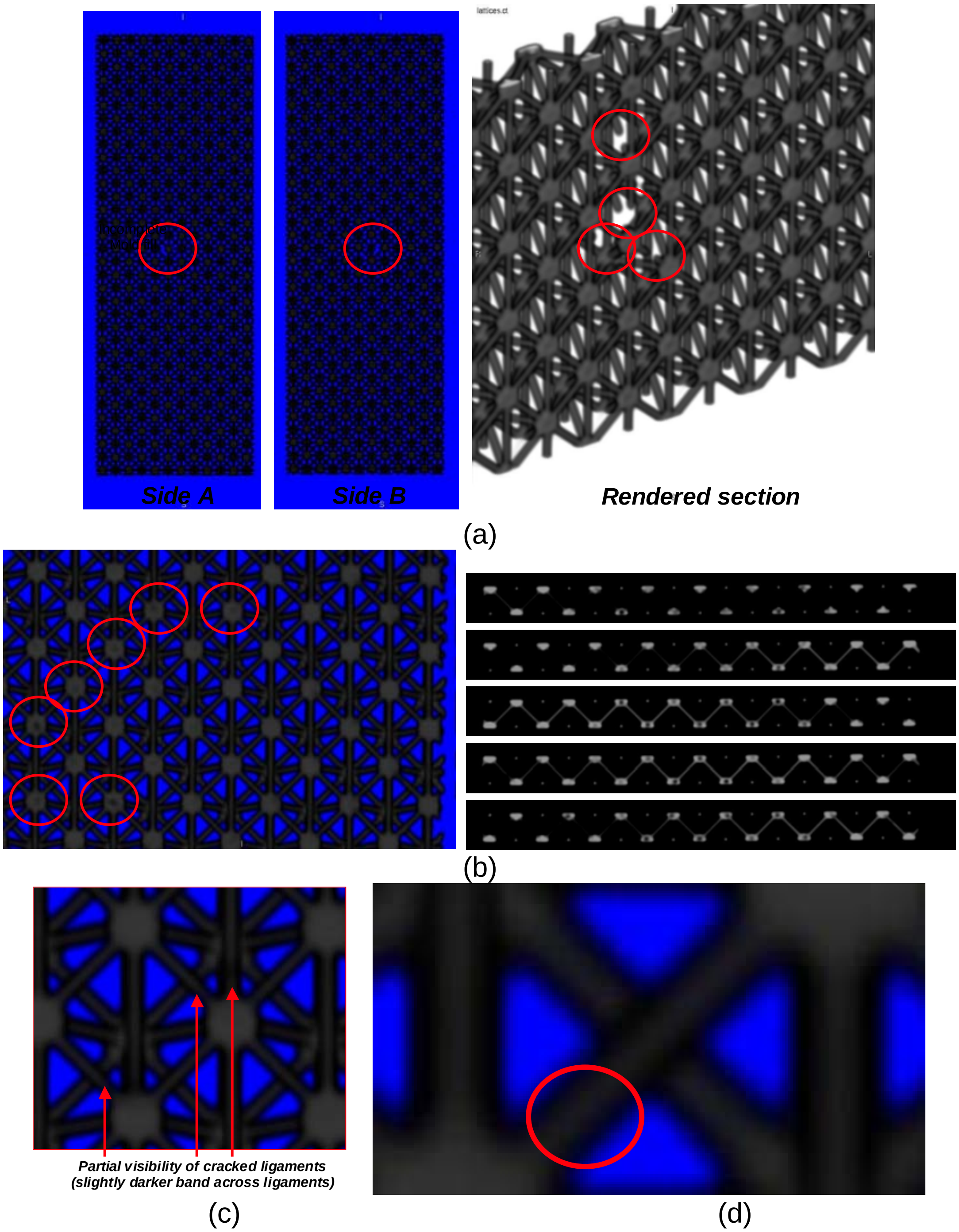


Figure 3.8: Radiographic inspection results using ICT techniques from the Alloy 718 LB with no face sheet including (a) detection of missing ligaments, (b) detection of likely node porosity, (c) partial detectability of cracked ligaments, and (d) lack of cracked ligament detection in other regions of the casting.

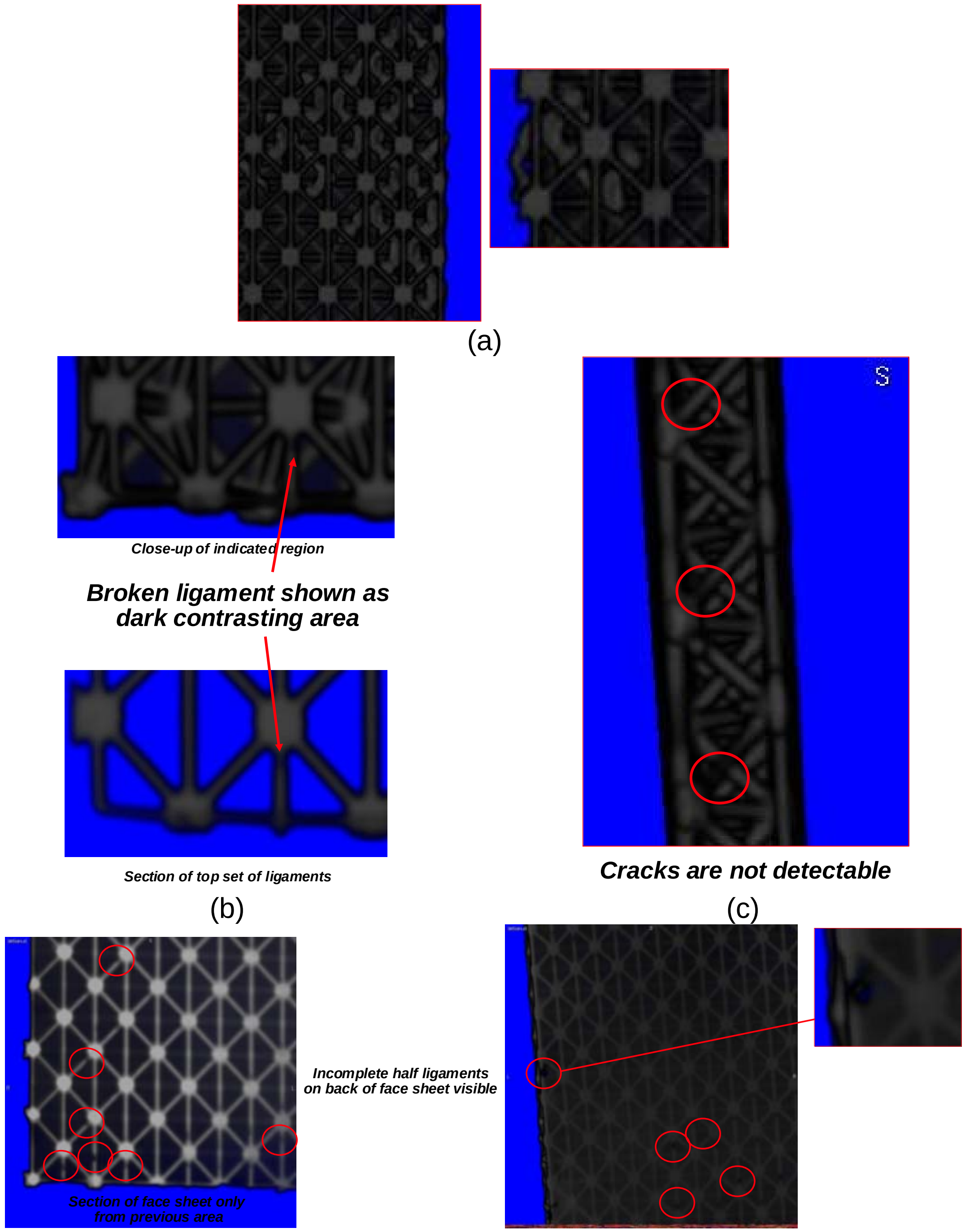


Figure 3.9: Radiographic inspection results using ICT techniques from the Alloy 718 LB with no face sheet including (a) detection of residual cast metal, (b) limited detectability of ligament cracking, (c) lack of cracked ligament detection, (d) detection of incomplete ligament fill adjacent to face sheet, and (d) detection of face sheet cracking defects.

Using high resolution ICT radiography techniques several defect types are detectable including missing ligaments, node porosity, residual cast material, incomplete filling of ligament sections, face sheet cracks, and some ligament cracks. Detection of ligament cracks is again, as in the case of UT inspection, not detectable with 100% certainty. Typical results using ICT radiography are shown in Figures 3.8 and 3.9.

As a result of the inspectability assessment, several limitations are evident. UT techniques have limited applicability due to their need to be in direct contact with the material surface in the region being examined. Radiographic techniques are able to detect several defect types, but are unable to reliably detect through thickness cracks within LB ligaments. Results of inspection characterization are summarized in Figure 3.10 for baseline material and Figure 3.11 for a variety of defects. LB structure capability and design material properties must take into consideration the limitations imposed by inspection capability. Limitations in structure size and configuration were primarily attributed to castability limits. Additional limitations regarding inspectability were also indicated and, as a result, the net effect of potential defects and defect distributions must be taken into consideration in the design and structural analysis of cast LB structures. Some analysis work has been performed on similar structures by Wallach and Gibson [10].

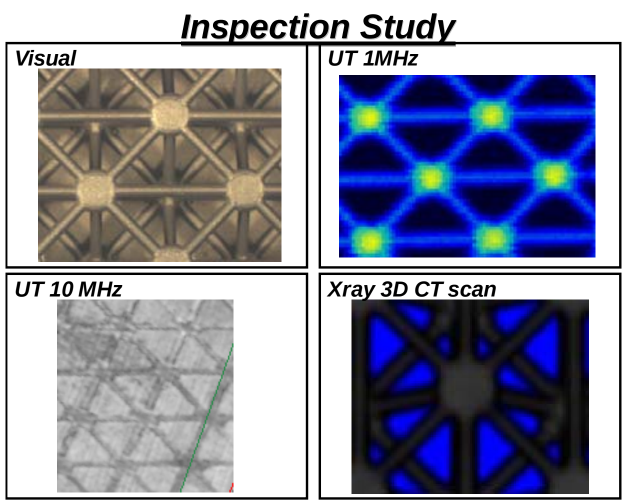


Figure 3.10: Detailed comparison of inspection techniques for areas with no defects.

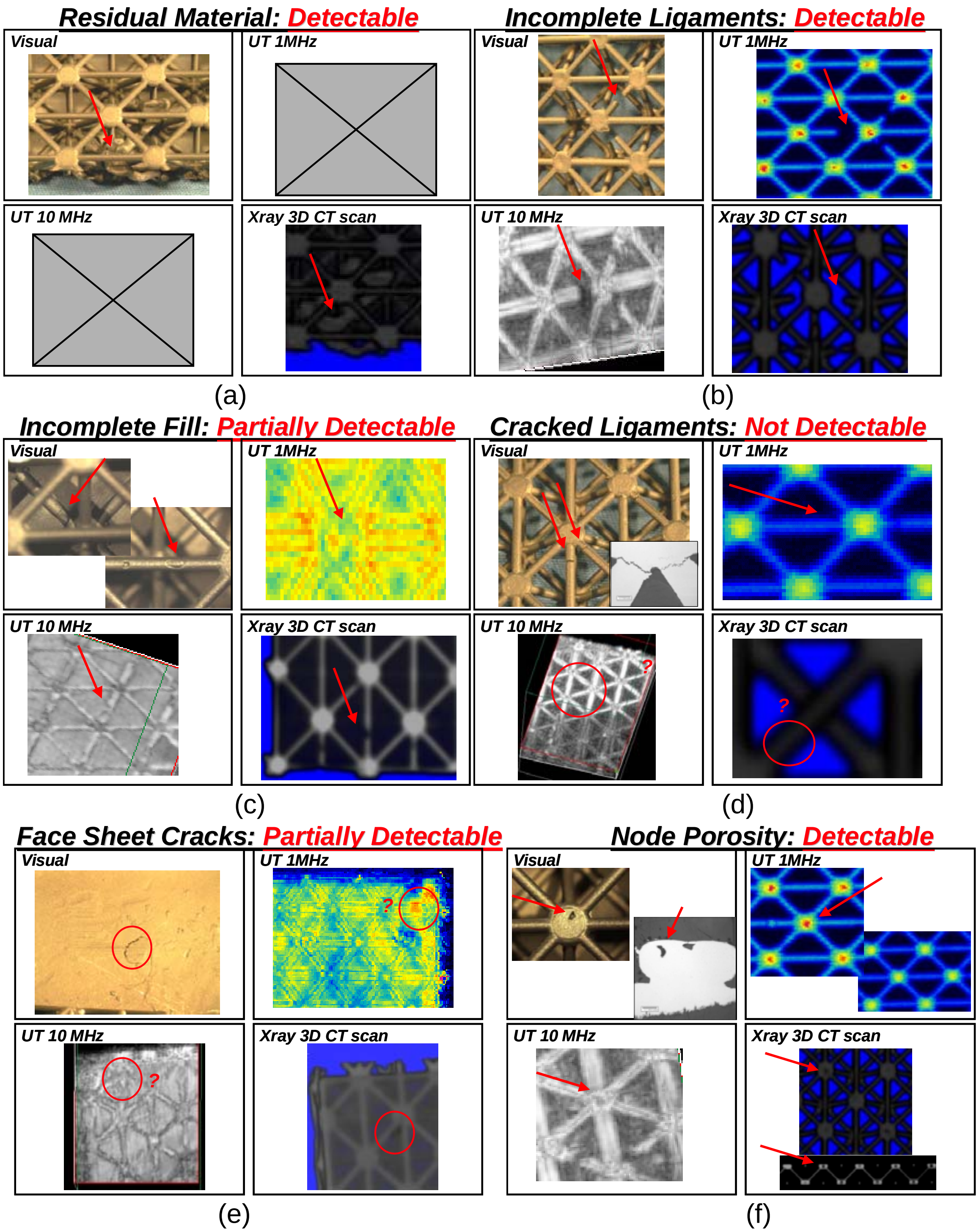


Figure 3.11: Detailed comparison of inspection techniques and ability to detect defects including (a) residual material, (b) incomplete ligaments, (c) incomplete fill, (d) cracked ligaments, (e) face sheet cracks, and (f) node porosity.

3.3 Assessment of Structural Capability:

An estimation of the mechanical capability was performed though a combination of metallurgical assessment, industry experience with conventional casting processes and geometries, and literature review. Example superalloys of interest for analysis are given in Table 3.3. Analysis suggests that, for geometries similar to that in the panels produced for NASA by Jamcorp™, Inc., typical cast material properties for alloys such as Alloy 718 and MarM247 alloys must be balanced against several other factors which affect properties. Factors include: LB geometry, fraction of structure filled with solid (effective density), relevant orientation with respect to the LB structure, the probability of casting-related defects which are not detectable by non-destructive testing techniques, the degree of sensitivity of the LB structure to such defects, and the effect of casting conditions on the overall component structure.

Table 3.3: Typical superalloys of interest for aircraft gas turbine engines

	Example alloys
• *Casting alloys*	
•*High hardener content alloys*	*MarM-247*
•*Weldable high temperature alloys*	***Alloy 718***
•*Wrought alloys*	
•*High strength*	***Alloy 718***
•*Sheet alloys*	*Hasteloy X*
•*High temperature alloys*	*HS 188*
• *Mechanically alloyed materials*	
•*Nickel-based ODS alloys*	*MA-754*
•*Iron-based ODS alloys*	*MA-956*

Several published studies [7-10] have examined the aspects of mechanical capability estimation based on experimental and/or modeling efforts. Additional studies [4,6] have assessed mechanical capability of superalloy LB structures. The results of these published studies have been integrated into the mechanical capability assessment. Assessments of properties for the cast material and the LB structure already being performed by NASA and by other authors, have also been integrated into this overall mechanical capability assessment. Estimates of effective density for a variety of LB structure dimensions with the tetragonal truss core structure are given in Figure 3.12, based on calculations found in Wallach and Gibson [8] for LB structures with no face sheets.

Analysis of typical microstructures from the Alloy 718 and MarM247 LB panels examined in this study, shown in Figure 3.13, suggest that material grain sizes are significantly less than that seen in castings produced using conventional casting processes and component geometries. A comparison to typical cast structure size is given in Figure 3.14. Refinement of the cast structure compared to conventional castings is likely a result of casting metal pour temperatures, section size, and cooling rate after casting. Several fine grained casting processes have been developed including Microcast-X® and Grainex® techniques [19-20]. Published data [19,21-24] from these processes and from conventional casting processes was used to estimate LB bulk material properties.

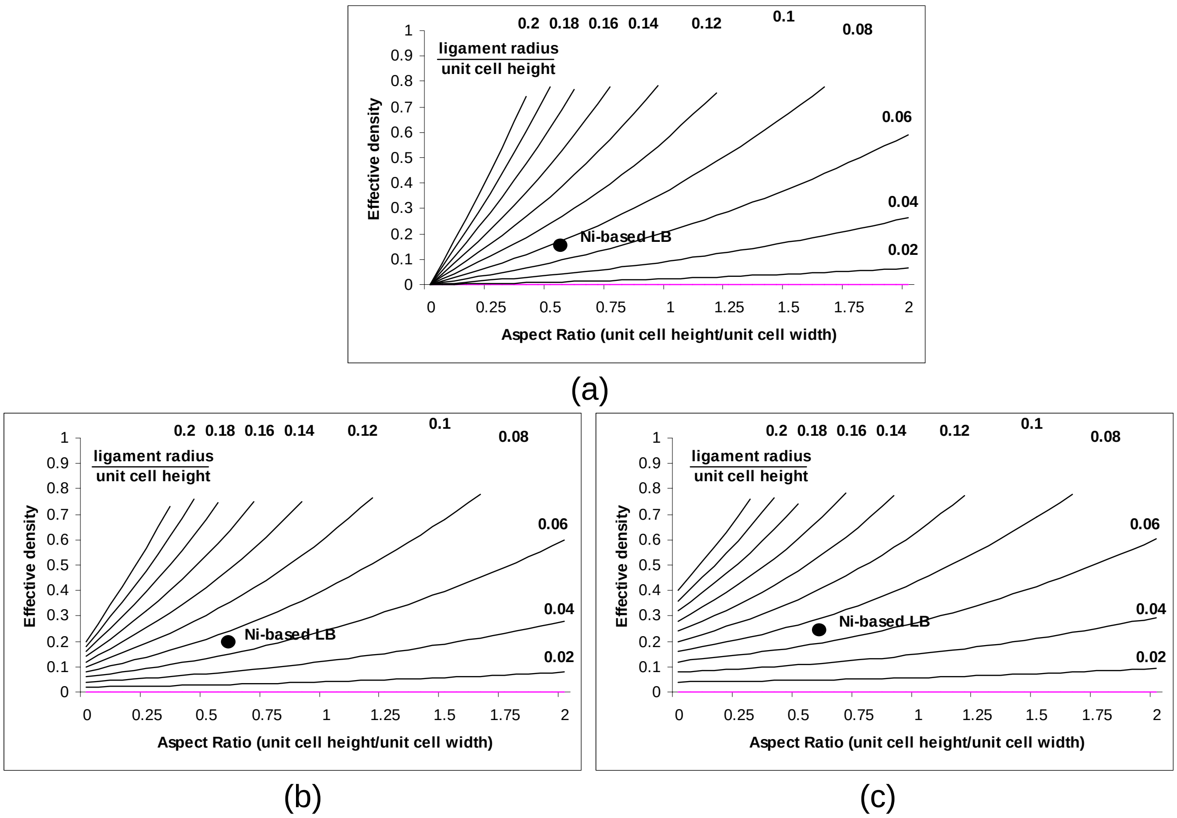


Figure 3.12: Estimation of effective structure density based on a pyramidal geometry, shown in Figure 1.3, defined by Gibson and Wallach [8] for LB structures with (a) no face sheets, (b) one face sheet with thickness equal to ligament radius, and (c) two face sheets.

Assessment of the grain size dependence of mechanical properties in Alloy 718 was performed for critical properties including tensile, fatigue and creep rupture based on available literature data [19,21-24]. A summary of grain size effects and estimated LB base material capability are indicated in Figure 3.15. Similar relationships are likely for MarM247 and other cast nickel-based alloys. Literature data [22] also suggests that the fine structure of LB castings may enable a modulus benefit similar to that observed for MarM247, shown in Figure 3.16.

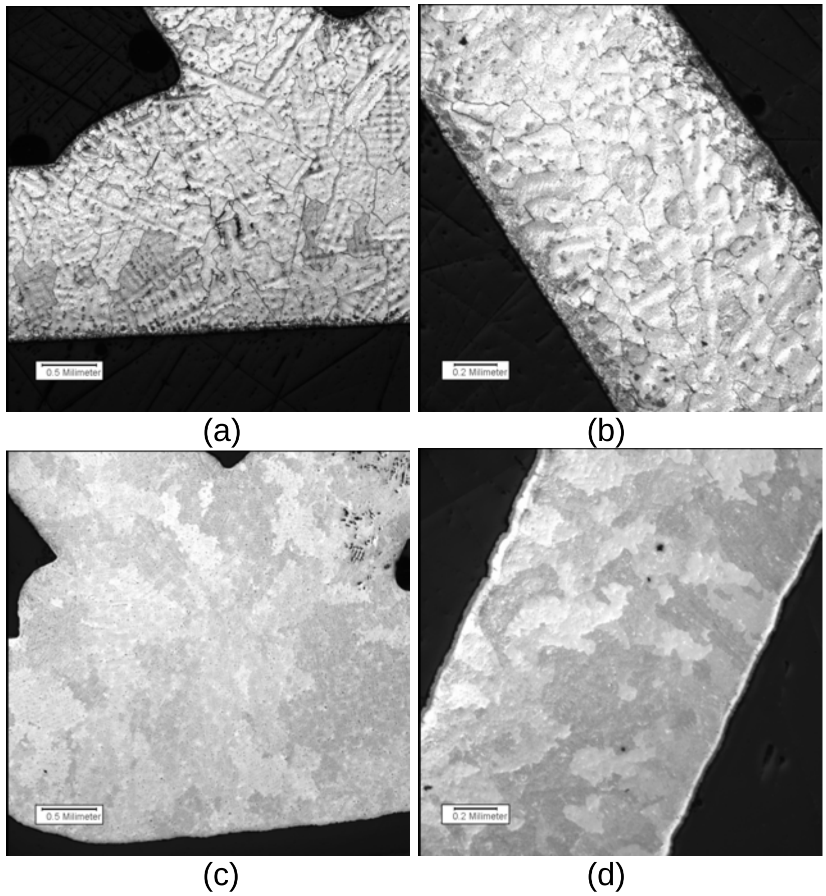


Figure 3.13: Typical microstructures for Alloy 718 (a) outer nodes and (b) inner ligaments and MarM247 (c) outer nodes and (d) inner ligaments from example panels provided by NASA.

Conventional Casting ***Thin wall casting (core ligament)***

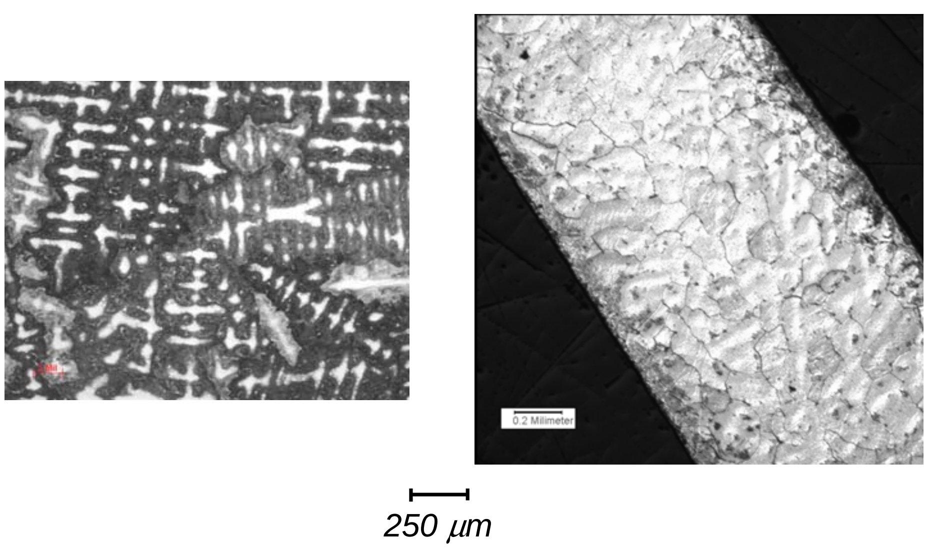


Figure 3.14: Comparison of structure sizes in conventional cast Alloy 718 material and lattice block structure ligament.

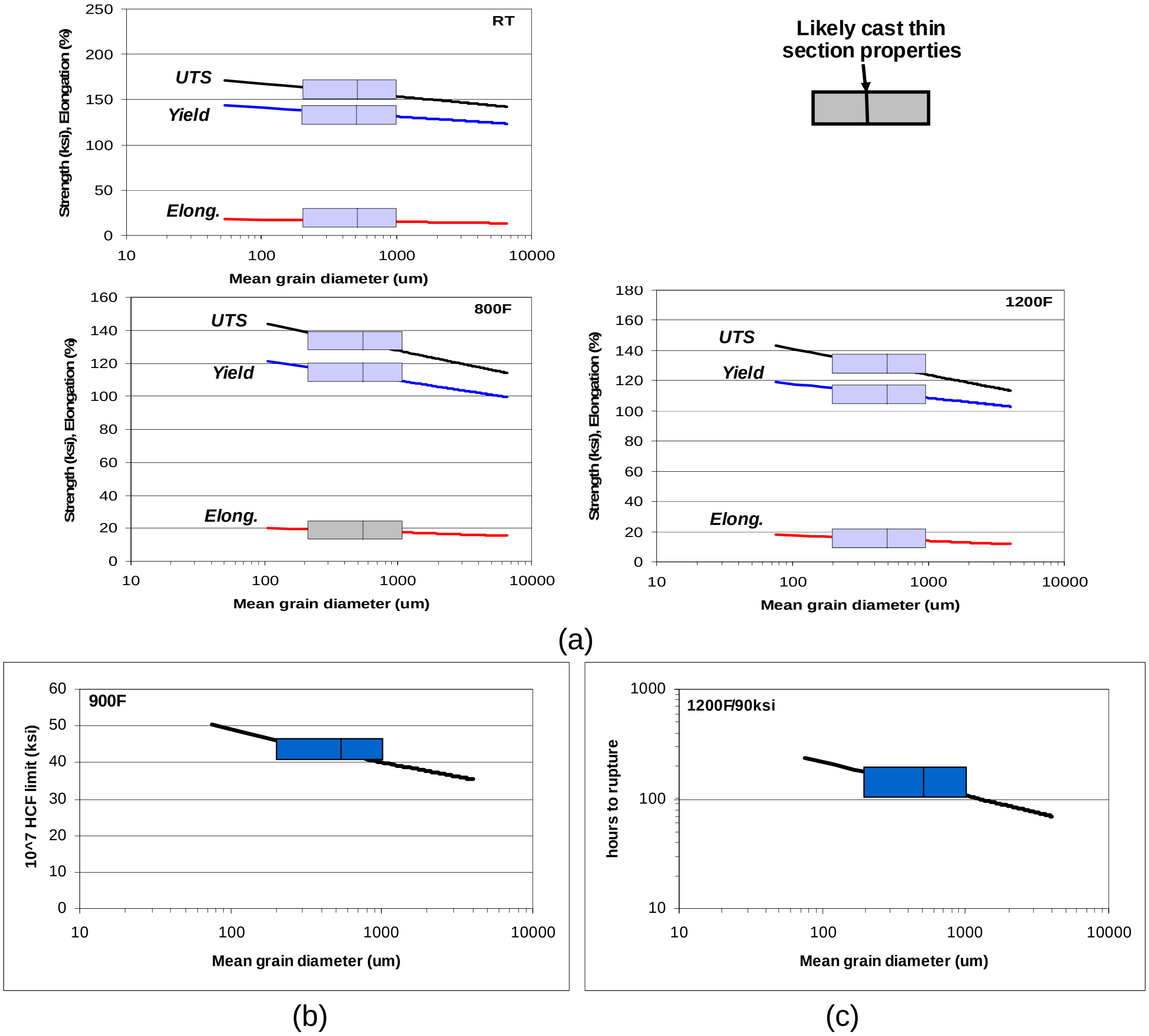


Figure 3.15: Compilation of literature data [19,21-24] for grain size effects in structural Alloy 718 castings and estimation of LB material capability ranges for (a) tensile properties at ambient, 800°F, and 1200°F, (b) fatigue at 900°F, and (c) creep rupture at 1200°F.

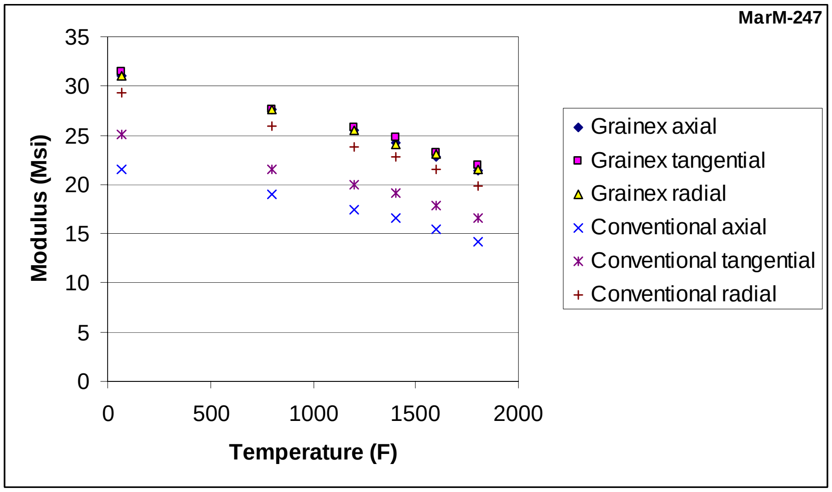


Figure 13.16: Improvements in modulus average and orientation dependence utilizing fine grained MarM247 castings [22]

3.4 Application Selection and Risk Analysis:

Several categories of potential applications including: casings, shrouds, frame struts and liners, exhaust system components, and other smaller actuator and flow control hardware were considered during this study. Potential engine applications envisioned were primarily related to applications for longer-term component upgrades and new designs on advanced commercial and military platforms were also discussed. Candidate components were identified from several component categories including high temperature fan and compressor applications, turbine applications, and exhaust nozzle structures. A summary of potential applications, engine system type, potential benefits and high-level requirements is given in Table 3.4. Elastic bending resistance (stiffness), strength, fatigue, thermal behavior, and ballistic impact resistance (containment) are among the application requirements of importance for various applications. Table 3.5 summarizes potential applications and an analysis of the implementation risk and payoff for using a LB structure. Bold-faced type is indicative of components with the best balance of perceived payoff and implementation risk. These components were considered in more detail in the remaining effort.

Table 3.4: Summary of potential applications, engines, potential benefits and high level requirements.

Applications	Engine(s)	Potential Benefits	Matl. & Process Requirements
Fan case	High Mach Supersonic	weight, stiffness	Containment, stiffness, strength
Fan duct	High Mach Supersonic	Weight, stiffness	Stiffness, strength
Compressor vane actuator rings	High Mach Supersonic	Weight, stiffness	Stiffness and fatigue
Mid frame and rear frame stiffeners	Conventional commercial & industrial	Weight, stiffness /strength	Stiffness, thermal control
Hot section liners shrouds, and struts	All engine types	Improved thermal management	Temp. capability, thermal control, thermal & mechanical fatigue
HPT Cases	All engine types	Improved thermal management, weight	Containment and fatigue
Augmentor ducts and duct stiffeners	Augmented Designs	Stiffness, improved thermal management	Stiffness, strength
Convergent afterburner flaps	Conventional military, High Mach Supersonic	Weight, stiffness	Stiffness, strength, integral cooling capability
Exhaust nozzle structures	High Mach Supersonic	Weight, stiffness	Stiffness, strength
Exhaust nozzle actuator rings	Conventional military engines	Weight, stiffness	Stiffness, strength

Table 3.5: Potential LB applications ranked by overall risk and payoff levels

Applications	Overall Risk Rank(H,M,L)	Perceived Payoff Rank
Compressor vane actuator rings	L	L
Mid frame and rear frame stiffeners	L	L
Exhaust nozzle actuator rings	L	L
Fan duct	**L**	**M**
Augmentor ducts and duct stiffeners	**M**	**M**
Convergent afterburner flaps	**M**	**H**
Divergent afterburner flaps	**M**	**H**
Exhaust nozzle structures	**M**	**H**
Hot section liners, shrouds, and struts	H/M/L	H/M/M
HPT Cases	H	M
Fan case	H	H

4.0 Application Requirement Identification:

Analysis techniques for assessing behavior of LB elements in a structure under complex loading conditions are not currently available. As a result, design concept generation of LB configurations desired in candidate components was difficult. This issue impacts the ability to assess material and process requirements at the LB substructure level. However, high-level design requirements have been assessed for selected potential applications considered in this study. A summary of these requirements is shown by component in Table 4.1.

Table 4.1: Summary of selected LB potential applications and resulting requirements.

Application	Max Temp	Likely Mtl.	Geometry	Dimensions	Casting or fabrication	Primary requirements
Supersonic divergent nozzle	<1200F	Alloy 718	Wedge (Beams plus face sheets)	44 inch long x 56 inch wide x 5.5 inch height	Possible mix of casting & fabrication	Pressure 11.3 psi (35ksi bending), 127.3 lb/in beam load
High Mach bypass duct	1150F	Alloy 718	Cylindrical to slightly conical	40+inch dia. x up to 3 feet long	Fabrication likely	Flowpath pressure, bending/buckling
High Mach convergent flap	N/A	Alloy 718	Actuated wedge/sheet with liner	70 inch wide x 30-50 inch long	Fabrication	Integral fluid cooling system, pressure loading

5.0 Assessment of Component Benefits:

A benefit assessment was performed for selected components identified in this study in order to quantify the effect of designing with LB structures. Potential benefits were identified for each component and one component was selected for detailed design analysis. Analysis was performed by making simple assumptions regarding the way the component would be constructed and by making simplifying assumptions concerning the mechanical behavior of the structure under typical application loading conditions.

5.1 Identification of Potential Benefits:

Potential benefits associated with candidate components were previously identified in Table 3.4. The preliminary assessment results were used to focus the Benefit Quantification effort to a more limited scope of components. Down-selection was performed based on perceived benefit level, component application risk, anticipated component producibility, and envisioned ability to meet material and process requirements, as well as anticipated engine insertion opportunities.

One such family of applications identified was exhaust nozzle structures. A divergent flap geometry relevant to the Long Range Strike Aircraft (LRSA) and also to the QSP was chosen for the preliminary analysis work. A sketch of this component is given in Figure 5.1. A similar design is also relevant to other engine system designs. In overall construction, the divergent flap is essentially a wedge-shaped structure approximately four feet on a side and approximately 6 inches in thickness tapering to near zero thickness. This flap concept is designed to have a pivot at the thick end of the wedge which would be actuated toward or away from the exhaust flow path during service. The baseline conventional structure considered in this evaluation consisted of a fabrication composed of I-beams, a continuous flow path surface sheet, and stringers. The I-beams form the thickness and taper of the component and cross the structure in both the length and width direction. They in turn provide support for the flow path face sheet. Stringers are placed between the beams to minimize sheet deflection in areas which span adjacent I-beams.

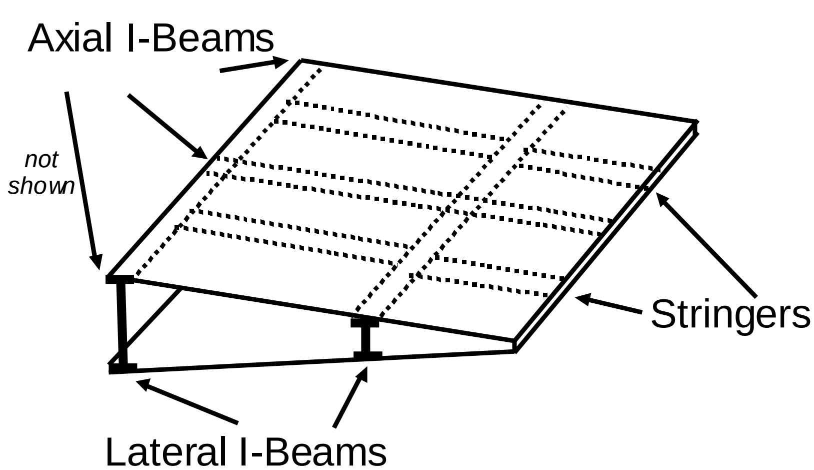


Figure 5.1: Sketch of a QSP/LRSA divergent flap

Preliminary analysis of several LB concepts was performed. Two construction concepts were examined for a given component application. In one concept, the large I-beam structure is replaced with a LB. In a second concept, the main structure was maintained as I-beams and the flow path surface and stiffening ribs were replaced by an LB with integral face sheets. Details of the analysis follow.

5.2 Exhaust Nozzle Benefit Quantification:

Component structural analysis and benefit quantification efforts focused on the LRSA divergent flap application. Currently analysis capability is limited, specifically in considering buckling behavior in the structural analysis. A detailed summary of the analysis work follows.

LRSA Divergent Flap Assessment:

A study was performed to identify potential applications of lattice block structure within an exhaust nozzle divergent flap design that could result in a weight benefit relative to a conventional flap design. The exhaust nozzle that was evaluated is a two-dimensional throat design. The divergent flap is approximately 44 inches long by 56 inches wide. The flap envelope thickness is 5.5 inches at the forward end, transitioning linearly to a 0.06 inch thickness at the aft end.

The flap is hinged at the fwd end and is driven by actuation linkages which attach to both sides of the flap approximately 30 inches aft of the forward end. The primary load is aerodynamic pressure loading which peaks at the fwd end with a ΔP of 11.3psi and decreases linearly to zero at the aft end.

The conventional design, incorporates axial I-beams along the length of the flap, which tie into a lateral I-beam at the forward end, transferring load into the sidewalls, and a lateral beam at 2/3 length, transferring load into the actuator links. A facesheet and stringer assembly is fixed to both sides of the beam flanges. The facesheets are 0.030 inches thick and form the internal and external flowpaths. The stringers support the facesheet, and are oriented laterally between axial beams.

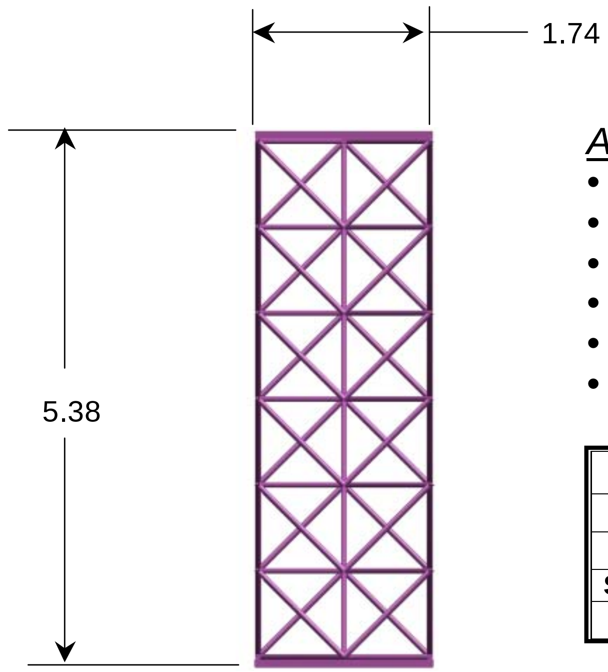
Two components of the flap have been evaluated using a lattice block structure - the fwd lateral I-beam and the facesheet/stringer assembly. An impediment to the proper evaluation of the lattice block designs is the lack of data on lattice shear and buckling capability. Specifically, the bending failure mode of many lattice block configurations will be local buckling of the support ligaments on the compression side of the structure. Similarly, shear loads will drive local compressive forces in the ligaments which can cause localized buckling. In order to perform a weight-trade study, a correlation is needed which captures the local buckling capability of the lattice block structures for various facesheet thicknesses (including 0, 1 and 2 facesheets), cell sizes, cell aspect ratios, and even number of stacked cells to simulate a thick structure. These various geometries would have to be loaded along the key orientation angles: 0, 45, and 90 degree angles for instance. Load scenarios would include bending, shear, and compression in the various orientations. Preferably, failure would be correlated to a maximum stress based on a calculation assuming a simplified geometry. For instance, a test may show that a given sample of lattice structure without facesheets fails in 0 degree bending (outer fiber tensile and compressive stress oriented at 0 degree) at 2000 in-lb moment. Assuming a simplified structure, such as a honeycomb panel with facesheet thickness equal to the diameter of the lattice block ligaments, a simple calculation (assuming facesheets are simple tension-compression members) may result in a facesheet stress of 67ksi. Thus, for preliminary design trades, we could say that a similar lattice block structure (same cell size/aspect ratio and facesheet geometry) could be expected to carry load to 67ksi effective stress based on the simplified honeycomb panel calculation.

While some data has been published, reports on testing of the full range of geometry and loading conditions described above along with data in sufficient detail have not been located. For most exhaust nozzle components, the requirements for bending moment capability would require that the lattice block have facesheets fixed to both sides. With one or no facesheets attached, the lattice block cannot match the bending capability to weight ratio of an I-beam structure. Little or no data has been found for this configuration. Without the required data, the lattice block concepts of this study have been sized based on bending capability, only, neglecting shear and bucking capability.

(a) Forward Lateral I-beam

This component is a 5.38 inch tall I-beam. The material is Alloy 718. It is simply supported at both ends and is subjected to a 127.3 lb/inch distributed load. For the baseline design, the I-beam geometry provides an extremely weight efficient bending stiffness. Due to the tall beam height, the flange and web thickness are limited by buckling capability of the shear web, rather than by bending stress. In this application, replacement of the shear web with a lattice block structure could provide a weight benefit if the lattice can support the shear load with less material weight.

This type of beam, shown in Figure 5.2, was evaluated. The beam consists of a beam height of 6 lattice cells with a flange brazed or welded to both the top and bottom. A ligament diameter of 0.060 inches was selected, as it is considered the minimum diameter producible in a medium to large casting. The cell dimensions are 1.74 inches wide by .87 inches tall. This 2 to 1 aspect ratio provides a diagonal ligament angle of 45^o. A weight summary for both beam designs is also shown in Figure 5.2. The lattice block beam, sized for bending capability only, provides a 30% reduction in weight relative to a conventional I-beam. The lattice block beam may or may not have sufficient shear and buckling strength.



Assumptions:
- *Alloy 718 material*
- *127.3 lb/in³ bending load*
- *0.06 inch ligaments and face sheet*
- *sized for bending only*
- *no consideration of buckling or shear*
- *cost aspects not considered*

	Weight Comparison	
	Baseline	Lattice Block
Flange	1.6688	2.753
Shear Web	7.8616	3.927
Total	9.5304	6.680

Figure 5.2: Analysis of the Forward Lateral Beam Cross-section using LB structures.

(b) Facesheet Design

The conventional design uses a 0.030 inch thick facesheet supported by Z-stiffeners. All materials are Alloy 718. The 0.030 inch thickness is assumed to be the minimum thickness required to avoid handling damage. The Z-stiffeners, which are oriented in the transverse direction, are spaced axially as required to meet a stress of 112 ksi, which is consistent with Alloy 718 sheet stock at a 1200°F temperature. The axial spacing decreases with the decrease in pressure loading, with a maximum spacing of 4.5 inches. The Z-stiffeners are 1 inch tall with a 0.030 inch stock thickness. The total weight of the facesheet / stringer assembly is 34.3 LB.

For the lattice block concept, Figure 5.3, a weight advantage is sought based on the fact that a facesheet supported by the lattice structure can be significantly thinner than a facesheet supported by the widely spaced stiffeners in the conventional design. Also the lattice weight may be less than the weight of the stiffeners in the conventional design. The following lattice block geometry was evaluated:

- A single cell lattice thickness.
- Cell height (h) = 1.0 inch
- Cell width varied from 2.0 inch to 3.5 inch.
- Ligament diameter of .06 inch and .04 inch
- 0.012” thick facesheets brazed or welded to each side of the lattice block.

The lattice facesheet was evaluated for an applied ΔP of 11.32 psi.

Figure 5.4 summarizes the resulting weight and bending stress levels of the lattice facesheet structure with a 0.06” diameter ligament, which is assumed to be the minimum diameter producible in a medium to large casting. Lattice weight decreases significantly with increasing cell size, as the density of the lattice material is reduced. The gross bending stress is relatively insensitive to lattice density as the facesheet geometry and the cell height is held constant. The maximum stress level of 35 ksi is present at the forward end of the flap, only, where the pressure loading is the maximum of 11.3 psi. The stress will decrease in the aft direction as the ΔP approaches zero. This stress level is well within the .2% yield stress of 112 ksi for Alloy 718 sheet and 75 ksi for cast Alloy 718. The lattice cell height could be reduced because of the significant stress margin, but this will result in a weight increase if the cell aspect ratio is maintained by also decreasing the cell width. If the cell width is held constant, thereby increasing aspect ratio, the weight can be reduced, but the buckling capability may be compromised.

The facesheet local bending stress is well within the allowable stress in all cases. However, as the cell size increases, the risk of facesheet handling damage increases and would have to be evaluated further if the lattice geometry were sized to the higher range of cell size.

Assumptions:
- *Alloy 718 material*
- *Conventional 0.03 inch face sheet min thickness for handling damage relaxed*
- *11.32 psi pressure loading of face sheet decreasing to 0 at aft end*
- *no consideration of buckling or shear*
- *consider casting or wrought material construction*
- *consider 0.06 and 0.04 inch ligament diameters*
- *cost aspects not considered*

Figure 5.3: Analysis of the Face Sheet and Stringer Assembly using LB structures.

Not reflected in Figure 5.2, is the fact that the shear stress and buckling capability of the lattice varies with cell geometry. Figure 5.5 summarizes the ligament angle and ligament aspect ratio (L/D) as a function of cell width. Based on the fixed cell height of 1.0 inch, a cell width of 2.0 inches provides a ligament angle of 45^o and a ligament L/D of 23.6. This geometry would provide the greatest buckling capability but offers a weight benefit of only 7.7% relative to the baseline design. A cell width of 3.5 inches provides a weight benefit of 27.8% but with significantly less buckling capability. Evaluation of the ligament buckling capability is required to determine the actual weight benefit.

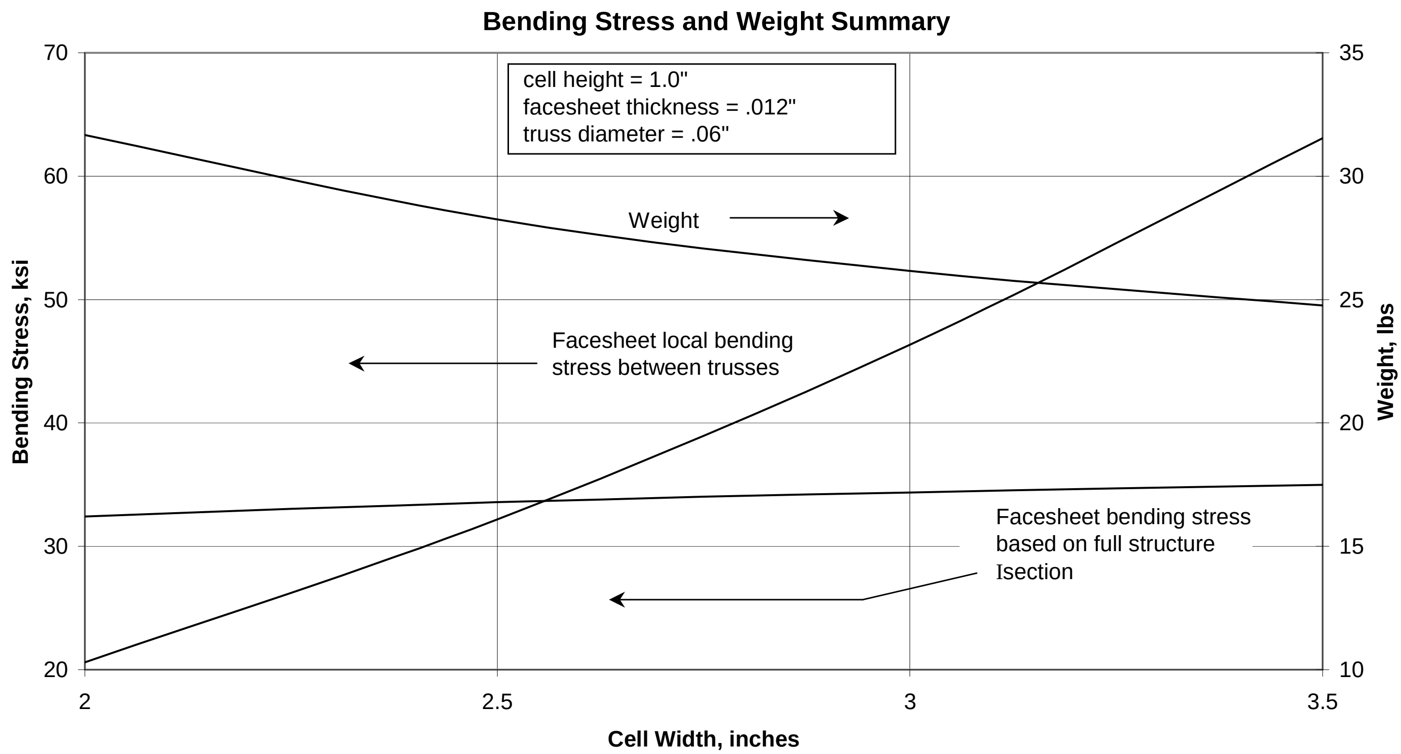


Figure 5.4: Bending stress and weight summary for 0.06 inch ligament diameters.

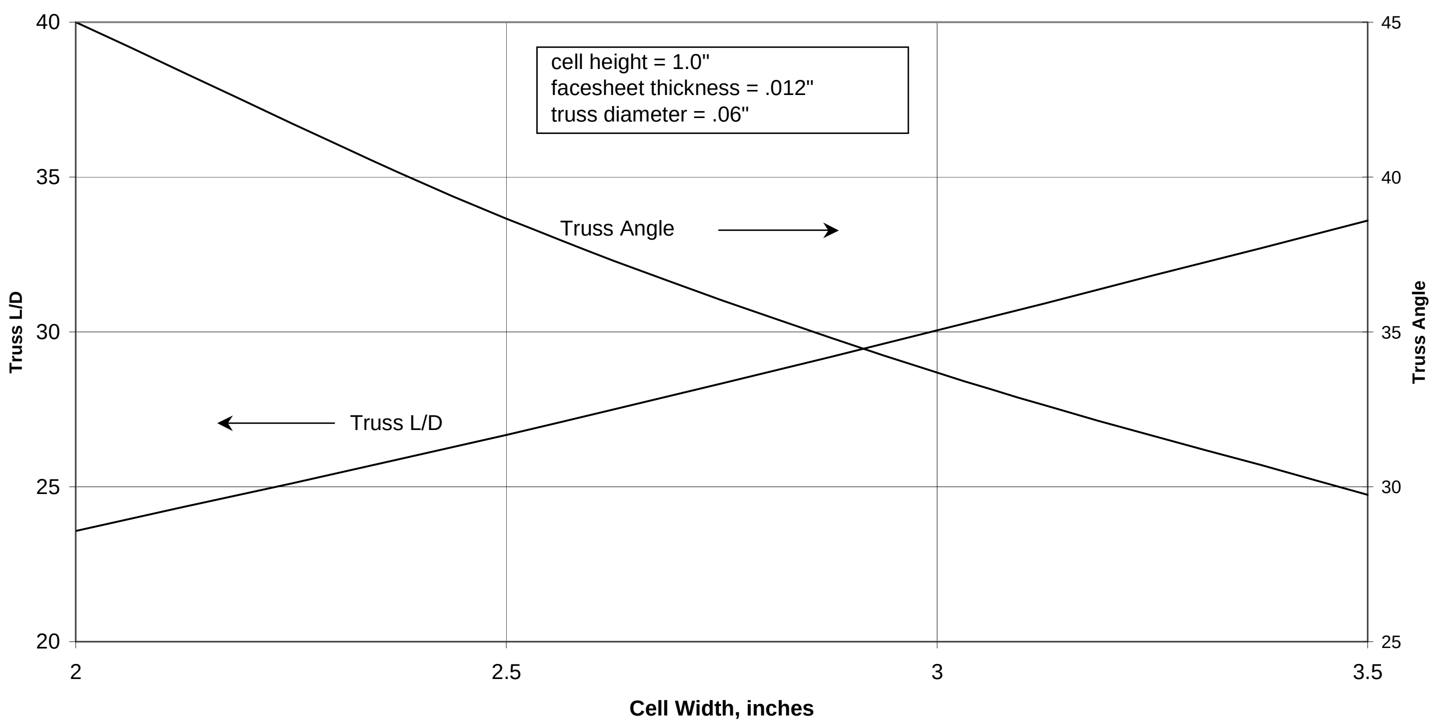


Figure 5.5: Ligament geometry for 0.06 inch ligament diameters.

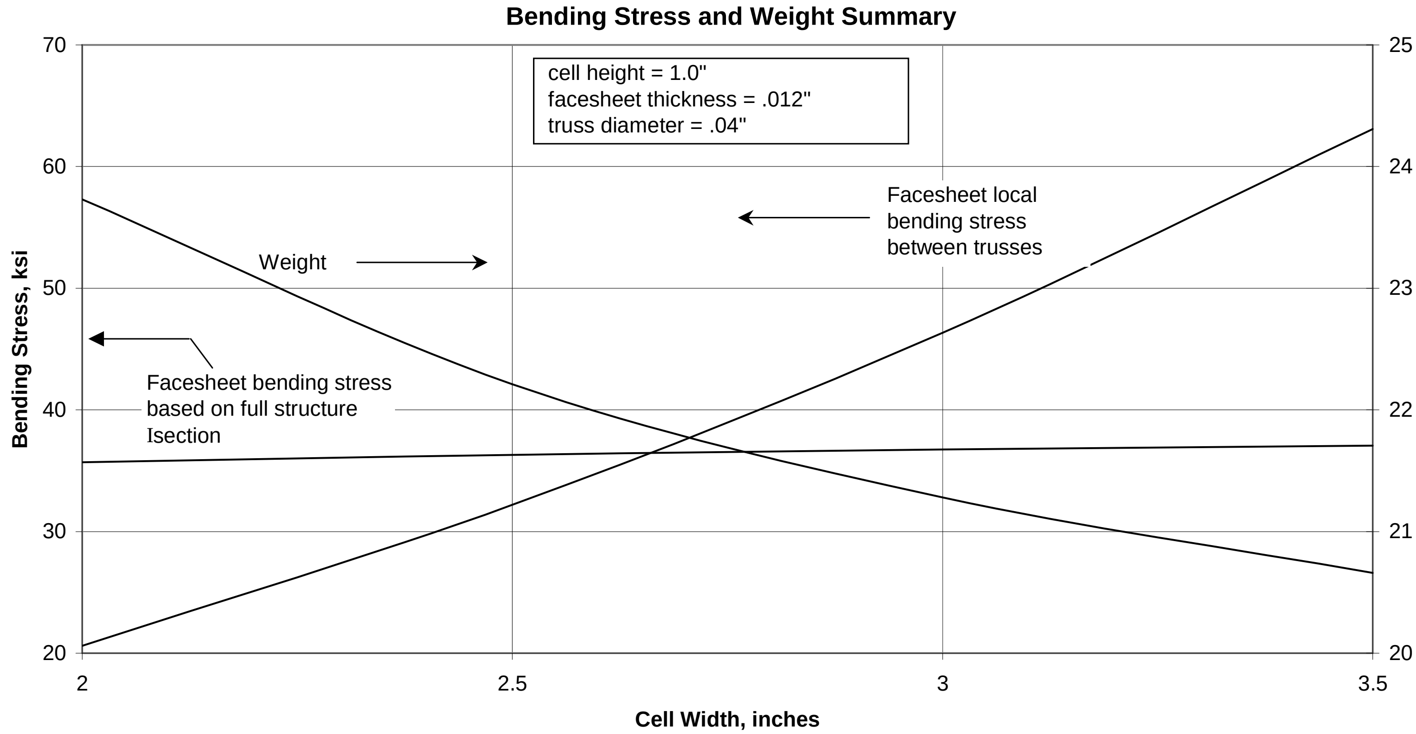


Figure 5.6: Bending stress and weight summary for 0.04 inch diameters.

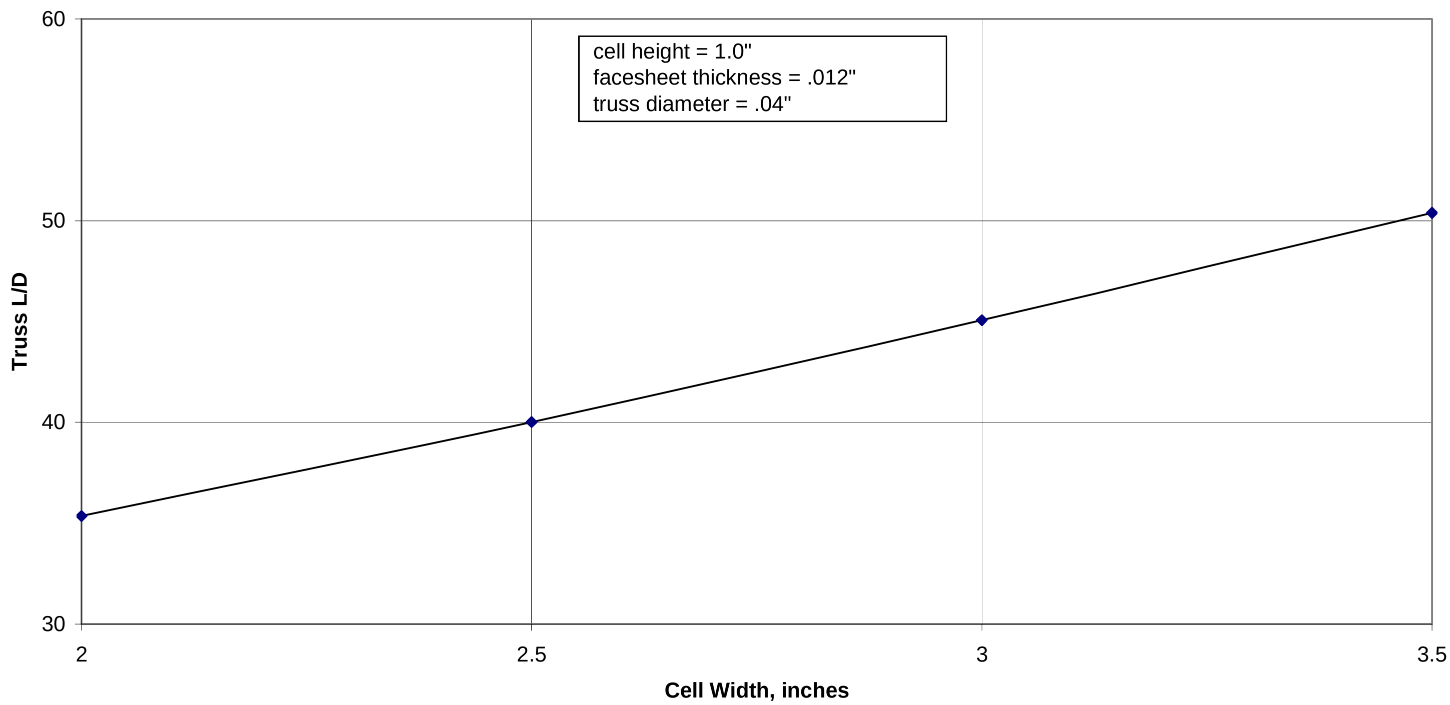


Figure 5.7: Ligament geometry for 0.04 inch ligament diameters.

The lattice facesheet was also evaluated using a 0.040” ligament diameter. A sheet metal forming process would most likely be necessary to achieve this ligament diameter. Figures 5.6 and 5.7 summarize the results of this study. The bending stress is only slightly higher than for the 0.060” ligament diameter. The weight for a 2.0 inch cell size (1/2 aspect ratio) is 23.7 LB or 31% less than the conventional design. However, this geometry would have significantly less buckling capability than the 0.06” configuration.

Limitations in available analysis tools to model mechanical behavior of candidate structures resulted in the benefit analysis being less extensive than originally planned. Additional assessment should be revisited on any follow-on efforts after appropriate design analysis tools become available.

6.0 Development of Demonstration Plan:

This task was discontinued prior to completion by mutual decision of GE Aircraft Engines and NASA. As a result of this assessment study, potential component applications have been identified which are of interest to the GE Aircraft Engines Revolutionary Turbine Accelerator (RTA) NASA program. Barriers to structural analysis of LB components encountered during this effort, particularly for more complex loading conditions, suggest that planning and pursuit of a demonstration component test program is premature. Instead, the more immediate go-forward plan should be structured primarily around a more detailed coupon testing program for envisioned component LB geometries under various loading conditions and integration of these test results with additional modeling efforts to enable continued development and validation of analysis techniques for LB structures. Some of this work is already ongoing through other NASA efforts for LB structures, however, assessment of more specific geometries and complex loading conditions envisioned for component geometries considered in this study are needed before a more clear component demonstration plan can be outlined. Overall high-level features of a development and demonstration plan follow. These recommendations should be considered as an outline for future efforts.

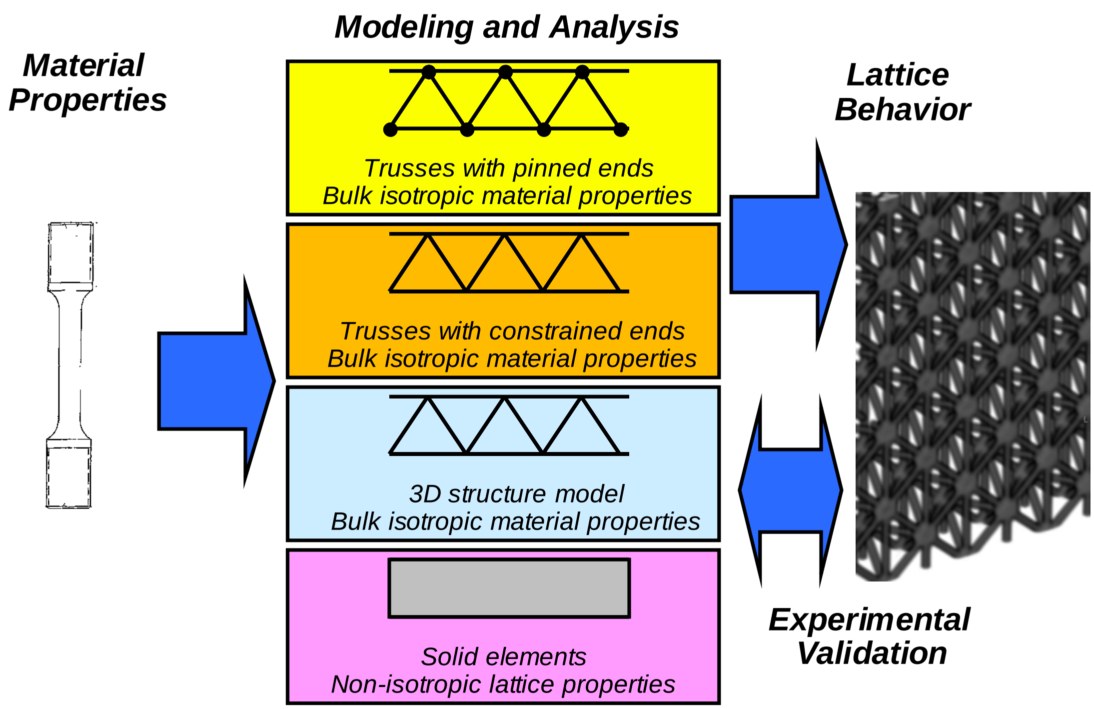


Figure 6.1: Potential approaches for development of analytical predictive capability for lattice structures.

6.1 Demonstration Plan and Component Opportunities

Based on the component-related analysis performed to date in this study, it is apparent that a more detailed design analysis study will be required. An ongoing need exists for development of analysis tools for computer modeling of lattice block structures based on existing approaches, Figure 6.1. Critical areas of need involve development of reliable structure analysis which account for buckling phenomena and aid in lattice geometry optimization in complex loading conditions.

An overall development and demonstration plan should include the following efforts:

(1) Augmentation of design analysis tools for complex loading conditions and complex component geometries
(2) Component feature panel testing, analysis, and validation
(3) Demonstration component design and manufacturing study
(4) Manufacturing process development, validation, and demo component manufacture
(5) Demonstration component rig/engine testing.

Several potential GE Aircraft Engines components are being considered for demonstration program planning including the LRSA divergent flap, the RTA bypass duct, and the RTA convergent flap.

6.2 Conclusions and Recommendations:

Based on the superalloy lattice block application assessment in the present study, the following conclusions were made:

- Superalloy LB structures may have potential application in high temperature fan and bypass cases and ducts, actuator assemblies, turbine shrouds, high temperature frames, and augmentor and exhaust nozzle components.
- Potential envisioned benefits of using the LB structure include reduced weight, increased stiffness, improved thermal management, reduced part count, and increased damage tolerance.
- Assessment of the producibility of LB structures made from superalloys was performed based on conventional casting capability. LB wall thickness lower bounds may limit design space for novel structures, particularly those with large thin walled LB areas.
- The fine cast structure in the thin walled LB ligaments may provide some additional property capability benefit over conventional cast material properties.
- The mechanical capability of the overall LB structure must be assessed based on bulk cast material properties, geometry and orientation effects, and the probability of undetectable defects and their net effect on overall performance through local load shedding and ligament structure behavior.
- Design analysis of the superalloy LB structures can be pursued using composite-type methodologies that account for orientation dependence of properties, or by modeling of complete LB 3-D truss structures during the design process. Various components may be more amenable to one approach than to the other.
- Continued efforts need to focus on determining LB structure properties, modeling the effect of defect distributions, and validating analytical methods with experimental techniques to assess relevant defect behavior and mechanical capability scaling factors which account for this behavior.
- Goals for successful application for an exhaust nozzle flap include
    - Weight reduction vs. conventional beam and stringer designs

    - Robust thin wall (0.06” or less) castings and/or wrought fabrications
    - Favorable system-level cost-weight trade analysis
- Projected benefits for a large exhaust nozzle flap include up to a 30% weight reduction potential, but additional analysis is still required.
- A technology demonstration plan must include
    - Casting and inspection process development
    - Assessment of geometry variability and defects on properties
    - Development of additional analysis tools and experimental validation
    - Manufacturing method cost analysis and trade study assessment

Some recommendations for continued work which was outside the scope of this assessment effort are as follows:

1. Investigate casting techniques and, where possible, effective non-destructive testing techniques in order to reduce the frequency of casting-related defects in cast LB structure.
2. Experimentally validate casting limitations with respect to minimum ligament diameter, face sheet thickness, and lattice geometry for both small and large component sizes.
3. Assess the effect of normal dimensional variability on mechanical properties in LB structures.
4. Continue to develop standard relationships between bulk alloy material properties and LB structure mechanical capability as a function of geometry using standard analysis tools and experimental validation. Properties of interest include modulus, tensile strengths, fatigue, and creep strengths at various temperatures.
5. Assess typical production costs for lattice block structure production via investment casting and by wrought fabrication methods.

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13. ABSTRACT *(Maximum 200 words)*

Robust, lightweight component designs are critical to aircraft gas turbine engine performance, efficiency, and application. Lightweight, superalloy lattice block structures composed of an open core with three-dimensional trusses have been examined as an alternative to bulk, fully dense, high-temperature static structures due to their strength, stiffness, and reduced weight. An assessment of the producibility and capability of these structures for aircraft gas turbine engine components suggests that the complexity of lattice block structure geometry may impose constraints upon the manufacturing method, design, and sizes of component structures produced. Preliminary analysis of an exhaust nozzle flap component indicates that weight reductions of up to about 30 percent may be achieved over conventional designs by integrating lattice block elements, but limitations in design analysis tools for these complex structures has prevented consideration of truss buckling in this analysis. Based on an application-focused assessment, recommendations are made regarding additional technical development needs envisioned before implementation of lattice block structures would be possible for aircraft gas turbine engine components.

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