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Zonal Lamination for Composite Parts in a Moving Line

Abstract

An apparatus and system is provided for fabricating composite parts. The system includes subdividing a laminate into zones, laying up tows of fiber reinforced material for the laminate over a layup mandrel via multiple laminations such that each lamination head applies tows in a different zone, and splicing the zones together to form the laminate during the laying up of the tows while moving the layup mandrel in a process direction during fabrication of the composite parts.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION [0001] This application is a Divisional of U.S. patent application Ser. No. 17/454,257, filed Nov. 10, 2021, and entitled “Zonal Lamination for Composite Parts in a Moving Line,” which claims the benefit of U.S. Provisional Patent Application Ser. No. 63/115,033, filed Nov. 18, 2020, and entitled “Zonal Lamination for Composite Parts in a Moving Line;” both of which are incorporated herein by reference in their entirety.

FIELD
[0002] The disclosure relates to the field of aircraft, and in particular, to fabrication of aircraft components.
BACKGROUND
[0003] Large composite parts, such as those spanning tens of feet, occupy substantial space within a factory floor. Laminates for these parts are laid up on a layup mandrel in a stationary work cell, where an Automated Fiber Placement (AFP) machine, comprising a massive end effector for a large robot arm, proceeds to add fiber-reinforced material on a tow-by-tow basis. The lone AFP machine traverses the entire part singularly according to an optimized layup pattern.
[0004] Present techniques for fabricating large composite parts therefore require a substantial amount of time in order for the layup mandrel to be indexed and then for a laminate to be laid-up. Therefore, it would be desirable to have a method and apparatus that take into account at least some of the issues discussed above, as well as other possible issues.
SUMMARY
[0005] Embodiments described herein provide for zone-based lamination which is accomplished via multiple lamination heads. By subdividing a laminate into zones and assigning the zones to different lamination heads that operate in tandem, overall production speed is enhanced. Furthermore, because the layup mandrel proceeds in a process direction during fabrication (e.g., by periodically “pulsing” in the process direction, or continuously moving in the process direction), the flow through the factory floor is enhanced. That is, transit time for a composite part may be utilized to perform work on the composite part, which enhances efficiency.
[0006] One embodiment is an apparatus for fabricating a composite part. The apparatus includes a lamination station that enables lamination heads to follow a contour of a layup mandrel that moves in a process direction during fabrication of a composite part, and lamination heads disposed at the lamination station are configured to lay up fiber reinforced material onto the layup mandrel, the lamination heads being configured to operate in tandem to lay up fiber-reinforced material for a laminate in different zones at the layup mandrel and splice the zones together. In one embodiment, the lamination heads operate in tandem to simultaneously lay up the fiber-reinforced material while simultaneously splicing the zones together.
[0007] A further embodiment is a system for fabricating a composite part. The system includes a track that follows the contour of a layup mandrel that moves in a process direction during fabrication of the composite part, a lamination station that includes lamination heads that are movably mounted to the track and are configured to lay up fiber reinforced material onto the layup mandrel. The lamination heads are configured to operate in tandem to simultaneously lay up fiber-reinforced material for a laminate in different zones at the layup mandrel while simultaneously splicing the zones together.
[0008] Other illustrative embodiments (e.g., methods and computer-readable media relating to the foregoing embodiments) may be described below. The features, functions, and advantages that have

been discussed can be achieved independently in various embodiments or may be combined in yet other embodiments further details of which can be seen with reference to the following description and drawings.

Description

DESCRIPTION OF THE DRAWINGS

[0009] Some embodiments of the present disclosure are now described, by way of example only, and with reference to the accompanying drawings. The same reference number represents the same element or the same type of element on all drawings.

[0010] FIG. **1**A is an illustration of an aircraft which can be manufactured with composite parts made in accordance with the methods, systems and apparatus described herein.

[0011] FIG. **1**B is a block diagram of a fabrication environment for laying up laminates that will be hardened into composite parts in an illustrative embodiment.

[0012] FIG. **2**A is a flowchart illustrating a method for laying up laminates in an illustrative embodiment.

[0013] FIGS. **2**B and **2**C depicts flowcharts illustrating methods for selecting splice locations at a laminate in illustrative embodiments.

[0014] FIG. **2**D is a flowchart illustrating a method for staggering cuts made for a splice in an illustrative embodiment.

[0015] FIG. **2**E is an end view of a splice at a laminate in an illustrative embodiment.

[0016] FIG. **2**F depicts overlapping angled butts between zones in an illustrative embodiment.

[0017] FIG. **2**G is an end view of a splice at a laminate in an illustrative embodiment.

[0018] FIG. **2**H depicts overlapping non-angled or straight butts between zones in an illustrative embodiment.

[0019] FIG. **3**A is a perspective view of a fabrication environment for laying up sections of fuselage in an illustrative embodiment.

[0020] FIG. **3**B is a side view of the fabrication environment of FIG. **3**A in an illustrative embodiment.

[0021] FIG. **4**A is a top view of a ply map for a laminate for a section of fuselage in an illustrative embodiment.

[0022] FIG. **4**B is a top view of a ply map for a laminate for a wing panel in an illustrative embodiment.

[0023] FIGS. **5-6** are perspective views of a fabrication environment for laying up wing skins in an illustrative embodiment.

[0024] FIG. **7** is a flow diagram of aircraft production and service methodology in an illustrative embodiment.

[0025] FIG. **8** is a block diagram of an aircraft in an illustrative embodiment.

DESCRIPTION

[0026] The figures and the following description provide specific illustrative embodiments of the disclosure. It will thus be appreciated that those skilled in the art will be able to devise various arrangements that, although not explicitly described or shown herein, embody the principles of the disclosure and are included within the scope of the disclosure. Furthermore, any examples described herein are intended to aid in understanding the principles of the disclosure, and are to be construed as being without limitation to such specifically recited examples and conditions. As a result, the disclosure is not limited to the specific embodiments or examples described below, but by the claims and their equivalents.

[0027] Composite parts, such as Carbon Fiber Reinforced Polymer (CFRP) parts, are initially laid-up in multiple layers that together are referred to as a preform. Individual fibers within each layer of the preform are aligned parallel with each other, but different layers exhibiting different fiber orientations can be used to increase the strength of the resulting composite part along different dimensions. The preform includes a viscous resin that solidifies in order to harden the preform into a composite part (e.g., for use in an aircraft). Carbon fiber that has been impregnated with an uncured thermoset resin or a thermoplastic resin is referred to as “prepreg.” Other types of carbon fiber include “dry fiber” which has not been impregnated. with thermoset resin but may include a tackifier or binder. Dry fiber is infused with resin prior to curing. For thermoset resins, the hardening is a one-way process referred to as curing, while for thermoplastic resins, the resin reaches a viscous form if it is re-heated.

[0028] Turning now to FIG. **1**A, an illustration of an aircraft is depicted in which an illustrative embodiment may be implemented. Aircraft **10** is an example of an aircraft **10** which is formed of half barrel sections **24** of fuselage **12**.

[0029] In this illustrative example, aircraft **10** has a wing **15** and a wing **16** attached to a body **38**. Aircraft **10** includes an engine **14** attached to the wing **15** and an engine **14** attached to the wing **16**. Each wing **15**, **16** has a tip **11** and a root **17**. Each wing extends from fore **19** to aft **23**.

[0030] Body **38** has a tail section **18**. A horizontal stabilizer **20**, a horizontal stabilizer **21**, and a vertical stabilizer **22** are attached to the tail section **18** of body **38**.

[0031] Fuselage **12** is fabricated from half barrel sections **24** with an upper half barrel section **26** joined to a lower half barrel section **28** to form a full barrel section **29-1**, **29-2**, **29-3**, **29-4**, **29-5**. The full barrel sections are joined serially to form fuselage **12**.

[0032] Wing **15** and **16** are each formed of a wing panel **30** comprising upper wing panel **32** and a lower wing panel **34** joined together.

[0033] FIG. **3**A is a perspective view of a fabrication environment **300** for laying up a half-barrel section preform **24-1** is depicted. In this embodiment, a layup mandrel **110** includes a surface **112** which has been precisely formed to a desired contour. The layup mandrel **110** also includes machined features **114** which facilitate indexing into half-barrel section preform **24-1** manufacturing excess **122**. A laminate **120** is laid-up onto the surface **112** as the layup mandrel **110** proceeds in the process direction **180**. For example, laying up a half-barrel section preform **24-1** is performed by lamination station **130** during pauses between micro pulses, pulses, or during continuous movement of the layup mandrel **110**. The laminate **120** includes a manufacturing excess **122**. The manufacturing excess **122** may receive indexing features via machining after the laminate **120** has been hardened, or may receive indexing features imparted by surface **112** into manufacturing excess **122**. Manufacturing excess **122** includes the strip shown on FIG. **1**B along with the door cut-out region **375** and window cut-out region **378** shown in FIG. **3**B.

[0034] The half-barrel section preform **24-1** discussed above is performed via lamination heads **134**, which are disposed along a track **132**. In one embodiment, the lamination heads **134** initiate tow **124**, **124-1** placement in one radial position, and work in a counterclockwise **65** direction until stopping. In one embodiment, the lamination heads **134** proceed to perform layup within their corresponding zones in a hoop-wise **66** direction as the lamination heads **134** perform coordinated sweeps in clockwise **64** or counterclockwise **65** directions (or both). In one embodiment, the lamination heads **134** initiate in one radial position, and work in a clockwise **64** direction until stopping at the far end. The lamination head **134** may perform multiple passes in this manner to apply multiple tows **124**, **124-1** at a variety of fiber orientations. The lamination head **134** is then paused until the next micro pulse, pulse, continuous movement of the structure and work in a clockwise **64** direction toward the starting point. The sweep of the lamination head **134** in one direction and then return in the opposite direction is an efficiency of motion which reduces movement to only what is necessary for placement of tow **124**, **124-1**. A single lamination head **134** can be removed and replaced, then receive maintenance while its replacement continues to perform.

[0035] The discussion provided herein is in no way limited to requiring all lamination heads to operate in the same direction at the same time. The zones provide herein make it possible for the lamination heads **134** to apply different layup orientation and/or patterns layups at the same time. This is particularly relevant, because different zones will perform different layup requirements in the form of different skin thicknesses, differing pad ups, the inclusion of doublers and sacrificial plies, etc. Thus, layup is not necessarily uniform from end to end or along hoop-wise **66** direction.

[0036] FIG. **1**B is a block diagram of a fabrication environment **100** for laying up laminates that will be hardened into composite part **55**, **55-1** in an illustrative embodiment. Fabrication environment **100** comprises any system, device, or component operable to utilize mobile lamination heads in a synchronous manner to perform layup of a laminate **120** onto a surface **112** of a layup mandrel **110** that proceeds in a process direction **180** during fabrication. The layup mandrel **110** would already have a plurality of stringers (not shown) placed longitudinally **181** into and forming part of the surface **112**. The stringers are placed upstream **181-1** of the lamination station **130**, **130-1**. The lamination station **130**, **130-1** layup upon the layup mandrel **110** and the stringers. The surface **112** forms a half barrel section preform **129** (i.e., a half-cylinder) when viewed from the end, and may define an Inner Mold Line (IML) **121** for a half barrel section preform **129**. In the view shown in FIG. **1**B, only the near side of the layup mandrel **110** and the laminate **120** are shown. Thus, the entirety of Zone two **117** is shown, only a portion of Zone one **115** is shown, and none of a far side Zone three **117-1** is shown. Reference is made to FIG. **3**A which shows Zone one **115**, Zone two **117** and Zone three **117-1** that are delineated by lines **319**. In this embodiment, the layup mandrel **110** proceeds along a track **132**, such as a layup mandrel **110** conveyance, during fabrication. The layup mandrel **110** may be pulsed incrementally such as a micro pulse of less than layup mandrel **110** length **181-7** or a pulsed of its entire length **181-7** in the process direction **180**. In such embodiments, work performed upon the layup mandrel **110** may be performed during pauses between pulses. In further embodiments, the layup mandrel **110** proceeds continuously in the process direction **180**. The layup mandrel **110** defines a contour **113**, **113-1** for a half barrel section **24** and a wing panel **30**, (FIG. **1**A) respectively. In further embodiments, the layup mandrel **110** defines an Outer Mold Line (OML) **521** (FIG. **5**) of a wing panel **30**.

[0037] A lamination station **130**, **130-1** lays up tows **124** of fiber-reinforced material (e.g., Carbon Fiber Reinforced Polymer or Carbon Fiber Reinforced Plastic CFRP) onto the layup mandrel **110** via multiple lamination heads **134**. In this embodiment, the multiple lamination heads **134** are disposed along a track **132** (e.g., a shared track), although in further embodiments the lamination heads **134** do not share a track **132**, but rather independently utilize one track **132** per lamination head **134** and hence lay up the tows from independent tracks. Furthermore, while only one lamination station **130** is shown in a longitudinal region **123**, **123-1**, multiple lamination stations **130**, **130-1** or lamination heads **134** may be arranged longitudinally **181** to perform work at the same time or synchronously in series. Furthermore, the lamination heads **134** may be arranged longitudinally **181** and/or circumferentially in series and/or in parallel. The tracks **132** may be provided at different offsets **135** from the layup mandrel **110**, and can be arranged such that a track **132** and a lamination head **134** are capable of passing by another track **132** and another lamination head **134** so as to improve versatility and avoid collisions, especially in splice zones **190**, **123-5**. The lamination heads **134** each follow a track **132** during layup, and may include internal actuators or other components (not shown) for facilitating movement across the track **132**, which itself may move longitudinally **181** relative to the layup mandrel **110**. In one embodiment, the track **132** complementary to the contour **113**, **113-1** of the layup mandrel **110**. During layup, the lamination heads **134** operate in tandem to apply tows **124** in a parallel process to layup in zone one **115**, zone two **117** and zone three **117-1** and/or longitudinal region **123**, **123-1** on the layup mandrel **110** in order to fabricate laminate **120**, which will be hardened into a half barrel section preform **24** or wing panel **30**. In this embodiment, the visible layer of the laminate **120** comprises forty-five degree tows **124-1**, although other layers may include tows **124** arranged at different fiber orientations than the tows **124** illustrated at zero degree orientation.

[0038] The lamination heads **134** may each operate in overlapping zones **191**, **123-2** with neighboring lamination heads **134.3921-1** Splice zones **190**, **123-5** at overlap zones **191**, **123-2** to be performed in a manner that enables the creation of splice zones **190** and **123-5**, without the risk of lamination head **134** collision. The lamination heads **134** operate in coordination to not just lay up the zone one **115**, zone two **117** and longitudinal region **123**, **123-1** but also to layup splices **392**, **394**, **395**, **392-1**, **394-1**, **395-1** in the splice zones **190**, **123-5** to form an integral laminate **120**. Furthermore, the lamination heads **134** may move at particular orientations (e.g., 0°, +/−45°, 90°, etc.), or may be specialized to lay tows at only one orientation. In one embodiment, different lamination stations **130**, **130-1** include different combinations of lamination heads **134**. For example, an upstream **181-1** lamination station **130-1** may include five lamination heads **134**, with one lamination head **134** for the zone one **115**, and two lamination heads **134** for each of zone two **117** and zone three **117-1**. A downstream **181-2** lamination station **130** may include three lamination heads **134** such as one lamination head **134** for the zone one **115**, and one lamination head for each zone two **117** and zone three **117-1**. In still further embodiments, the lamination heads **134** are used as end effectors of robot arms (not shown) that sweep across the laminate **120** without the need for a track **132**. The lamination head **134** would be paired with the robot arms in a one-to-one relationship.

[0039] In this embodiment, laminate **120** includes manufacturing excess **122**, which may receive indexing features such as holes, slots, or pins after it is hardened or formed into laminate **120** by surface **112** during layup and processing, in order to facilitate indexing of the composite part **55**, **55-1** to post hardening assembly work stations after the composite part **55**, **55-1** has been removed from the layup mandrel **110**. Unlike prior systems that relied upon one monolithic AFP machine, the fabrication environment **100** depicted in FIG. **1**B provides a technical benefit, divides the layup work into several regions amongst several lamination heads **134** and joins the regions together with splices because it reduces the size of a single layup region into as small region for efficiency, which enables multiple lamination heads to operate at once, and then unify borders between regions with scarf or step overlaps. Furthermore, the multiple lamination head **134** system described herein facilitates the use of smaller, lighter, specialized lamination heads **134** which are less complex than traditional AFP heads and therefore have less bulk to maneuver, and less complexity. This may permit the lamination heads **134** to move more quickly and more precisely, and also increases reliability and ease of maintenance.

[0040] The lamination heads **134** can be designed to perform a variety of movements relative to the layup mandrel **110**. For example, the lamination heads **134** can be moved while the layup mandrel **110** remains stationary, the layup mandrel **110** could be moved relative to fixed lamination heads **134**, or a combination of layup mandrel **110** and lamination head **134** movement relative to each other can be utilized to facilitate layup.

[0041] Track **132** has a contour complementary to the layup mandrel **110**, and may comprise a rigid track that is disposed at a known offset O from an indexing unit **136**. The indexing unit **136** mates with machined features **114**, for instance slots, blind holes, holes, pins, at the layup mandrel **110** in order to precisely index the layup mandrel **110** to the lamination station **130**, **130-1**. While only two lamination stations **130**, **130-1** are depicted in FIG. **1**B, in further embodiments more lamination stations **130**, **130-1** are arrayed in the process direction **180** (i.e., longitudinally **181**). In additional, in an embodiment, to lamination stations **130**, **130-1** on the pre-autoclave side is a vacuum bag installation station (not shown) followed by a caul plate installation station (not shown). Another embodiment has a caul plate performing the dual function of the caul plate and the vacuum bag. In one embodiment, a lamination station **130** downstream **181-2** of the current lamination station **130-1** includes a single lamination head **134** for performing any desired re-work or additional layup. The single lamination head **134** may perform additional layup that was missed if an upstream **181-1** lamination head **134** is lagging. In still further embodiments, each lamination station **130**, **130-1** is capable of moving back and forth in the process direction **180** to facilitate layup processes. In still further embodiments, fewer lamination heads **134** are disposed in zone one **115** than in zone two **117** or zone three **117-1**. As there is often a less complex layup and/or fewer plies in zone one **115**, fewer lamination heads **134** may be utilized for layup at a zone one **115** than in zone two **117** and zone three **117-1**.

[0042] FIG. **1**B further depicts a lamination server **170** which controls the operations of the lamination station **130**, **130-1**. In this embodiment, the lamination server **170** includes an interface **172**, optionally comprising wired connection **171** such as an ethernet interface, Universal Serial Bus (USB) interface or wireless interface for communicating with the lamination station **130**, **130-1** and/or indexing unit **136**. The lamination server **170** includes a memory **176** that stores one or more Numerical Control (NC) programs for operating the lamination station **130**, **130-1**. In one embodiment, the NC programs mitigate collision risk by ensuring that multiple lamination heads **134** do not operate close enough to each other to collide. Coordinating the operations of the more than one lamination heads **134** to ensure that multiple lamination heads **134** do not collide during operation. Pairing up one track **132** per lamination head **134** with various offsets **135** reduces the complexity of guiding the lamination heads **134** through overlap zones **191**, **123-2** by avoiding more than one lamination head **134** per one track **132** within overlap zones **191**, **123-2**. The various offsets **135** permits one track **132** to pass under another track **132**. In still further embodiments, the lamination heads **134** include sensors that detect proximity to other lamination heads **134**, and the lamination heads **134** are halted and/or moved away in the event that they come closer than a threshold proximity to each other. Controller **174** manages the operations of lamination server **170** by processing feedback from lamination station **130**, **130-1** and/or indexing unit **136**, and providing instructions based on such feedback. Controller **174** may be implemented, for example, as custom circuitry, as a hardware processor executing programmed instructions, or some combination thereof.

[0043] FIG. **1**B further illustrates a splice zone **190** between zone one **115** and Zone two **117** and similarly, there is a splice zone not shown between zone one **115** and zone three **117-1**. While the splice zone **190** is shown arranged longitudinally **181**, a circumferential splice (FIG. **1**B), such as hoop-wise, splice zone **123-5** disposed along the length **181-7** of the laminate **120** may be used at overlap region **123-2** between longitudinal region **123**, **123-1**. In further embodiments, splice zone **123-5** are omitted within zone one **115** of the laminate **120** as a single lamination head **134** on a dedicated track **132** with an appropriate offset **135** may apply all of the tows **124**, **124-1** negating the need to splice. Furthermore, while the laminate **120** is shown as short length **181-7** in relation to its height **181-9**, in one embodiment the laminate **120** length **181-7** extends, for example, twenty-five feet and in another embodiment the length **181-7** extends up to forty feet or longer. Thus, a first set of lamination heads **134** in lamination station **130** may lay up plies **126** at a first region R**1** along a length **181-7** of the laminate **120**. First region R**1** would coincide with longitudinal region **123**. Then, the laminate **120** is micro pulsed in a process direction **180** until the longitudinal region **123** reaches coincides with second region R**2** and within the purview of another set of lamination heads **134** in lamination station **130-1** while at the same time longitudinal region **123-1** micro pulses to coincide with third region R**3** (not shown) and into the purview of lamination station **130-**N (not shown). Similarly, the mandrel is advanced in process direction **180** from lamination station **130**, **130-1** to lamination station **130-**N until laminate **120** is completed. Micro pulse is an advancement of the layup mandrel **110** and laminate **120** by less than length **181-7** in process direction **180**. In the illustrated embodiment, the micro pulse is about half the length **181-7**. Other embodiments with more closely arranged lamination stations (**130**, **130-1**) have a micro pulse of about one third or less of the length **181-7**. A full pulse is an advancement of the layup mandrel **110** and laminate **120** by its length **181-7** in process direction **180**. After the micro pulse, first region R**1** becomes second region R**2** and the lamination station **130-1** builds upon the tows **124** placed by lamination station **130** in the first region R**1** by adding additional tows **124**, **124-1** thereto while the lamination station **130** lays down plies **128** for a next region R**2** of the laminate **120**. Furthermore, the lamination stations **130**, **130-1** and/or lamination heads **134** may be positioned and/or pulsing of the laminate **120** may be coordinated to enable operation within splice zones **190**, **123-5** as desired. Each splice may comprise a scarf splice (not shown, lap splice **392-1**, or step lap splice (not shown), and may vary in thickness as compared to un-spliced plies **396**, **397**, **398**.

[0044] Unlike layups using a single AFP machine which dispenses tows **124**, **124-1** for a ply of a laminate over length **181-7** and height **181-9**, the lamination heads **134** are each dedicated to the particular zone one **115**, zone two **117**, zone three **117-1** or longitudinal region **123** or **123-1** or sets thereof. This reduces the potential for collision risk while increasing layup efficiency. To accommodate this increased aggregate speed of layup using multiple lamination heads **134**, and to enable fabrication of a single integral laminate **120**, the particular zone one **115**, zone two **117**, zone three **117-1** or longitudinal region **123** or **123-1** are spliced together.

[0045] In some embodiments, as is shown in FIGS. **2**E-**2**H, the splice zones **190**, **123-5** have layup splices **392**, **394**, **395**, staggered by overlaps **399**, **399-1** from adjacent plies from plies **396**, to ply **398** to ply **397** and so on through laminate **120**. In this arrangement, tows **124**, **124-1** of individual plies within splice zones **190**, **123-5**, such as ply segment **393** are terminated at layup splice **392** with an angled butt **385**, **386** (see FIG. **2**F) and a non-angled butt **387**, **387-1** (see FIG. **2**H) configuration as part of a lap splice **392-1** with no separation or a small separation (e.g., a fraction of an inch) from ply segment **393-1** at layup splice **392**. The layup splice **392** has ply segment **393** and ply segment **393-1** cut and placed into a complementary angled butt **385**, **386** and a non-angled butt **387**, **387-1** configuration as part of a lap splice **392-1** with overlaps **399**, **399-1** staggering in relation to the layup splice **394**. This type of overlaps **399**, **399-1** staggering of subsequent layup splices **392**, **394**, **395** provides the lap splice **392-1** that facilitates load transfer through splice zones **190**, **123-5**. Another embodiment has the splice in a scarf or step lap configuration (not shown). All splice types require the ply segment **393** and ply segment **393-1** to be trimmed into complementary alignment. Ply **396** has a layup splice **392** staggered from the ply **398** layup splice **394** and so forth for each subsequent ply of laminate **120**. Furthermore, splice zones **190**, **123-5** are located in less complex or thinner portions of the laminate **120**, such as areas without window/door surrounds, pad ups or other complicated geometries. In this manner, splices are positioned between complex layup areas instead of within those areas. A splice may be thicker than the thickness of an un-spliced laminate **120**, and hence the splice may comprise staggered joins of one or more cuts portions of ply through the thickness of the laminate **120**. In further embodiments, the locations of cuts for individual plies **396**, **398**, **397** within a layup splice **392**, **394**, **395** are staggered relative to angled butt **385**, **386** and non-angled butt **387**, **387-1** for other plies in the splice zone **190**, **123-5**. This causes the layup splice **392**, **394**, **395** to be staggered across a distance of a multiple of overlaps **399**, **399-1**, which enhances load bearing properties of the lap splice **392-1**. Staggering the positions of cuts of plies within a splice zone **190**, **123-5** enhances the ability of the splice zone **190**, **123-5** to bear load there through when hardened into a composite part **55**, **55-1**. After receiving layup, the layup mandrel **110** proceeds to an autoclave **193**.

[0046] Illustrative details of the operation of fabrication environment **100** will be discussed with regard to FIG. **2**A. Assume, for this embodiment, that layup mandrel **110** has been indexed but has not yet received any composite material and has just begun to proceed underneath track **132**.

[0047] FIG. **2**A is a flowchart illustrating a method **200** for laying up laminates in an illustrative embodiment. The steps of method **200** are described with reference to fabrication environment **100** of FIG. **1**B, but those skilled in the art will appreciate that method **200** may be performed in other systems. The steps of the flowcharts described herein are not all inclusive and may include other steps not shown. The steps described herein may also be performed in an alternative order.

[0048] In step **202**, the layup mandrel **110** is moved in a process direction **180**, either continuously or in a pulsed fashion, to a lamination station **130**, **130-1** during fabrication of a composite part **55**, **55-1**. Receiving the layup mandrel **110** may comprise a first region R**1** of the layup mandrel **110** proceeding beneath the lamination station **130** or may comprise the layup mandrel **110** reaching a location where it may be indexed by the indexing unit **136**.

[0049] In step **204**, the indexing unit **136** indexes the layup mandrel **110** to the multiple lamination heads **134**. This may be performed by placing a complementary feature **136-1** at the indexing unit **136** into one or more of the machined features **114** at the layup mandrel **110**, in order to precisely determine a position of the layup mandrel **110** and surface **112** to the lamination station **130**. Because an overlap offset O **399** of the indexing unit **136** is precisely known, the position of the layup mandrel **110** relative to the lamination station **130**, **130-1** and any lamination heads **134** may be programmatically determined based on the position of the layup mandrel **110** relative to the indexing unit **136**. Based on this information, an NC program at the controller **174** may be updated to account for any discrepancies of the layup mandrel **110** or surface **112** from an expected nominal orientation/position. The layup mandrel **110** may be repositioned relative to lamination station **130** and/or NC program to eliminate such discrepancies.

[0050] In step **206**, laying up is subdivided into zone one **115**, zone two **117**, zone three **117-1** and longitudinal region **123**, **123-1** by controller **174** and/or N/C program. Within each zone one **115**, zone two **117**, zone three **117-1** and longitudinal region **123**, **123-1**, a single lamination head **134** will be operated. By creating such zone one **115**, zone two **117**, zone three **117-1** and longitudinal region **123**, **123-1** and limiting lamination head **134** movement to within the zone or region, layup may be performed independently by the lamination heads **134** at the lamination station **130**, **130-1** and/or further lamination stations **130-*n***, without the need for complex sensing and collision avoidance. That is, because the lamination heads **134** do not operate in each other's zones and regions, and because the actions of the lamination heads **134** are coordinated with respect to each other, there is no chance of collision when the lamination heads **134** are run in parallel. The collision avoidance occurs even in environments including overlap zones **191**, **123-2** in order to form layup splices **392**, **394**, **395**. For example, a controller **174** may direct its lamination heads **134** to operate on the forward portion **127-1** of the zone one **115**, zone two **117**, zone three **117-1** and longitudinal region **123**, **123-1** in parallel. The lamination heads **134** proceed to the aft portion **127** of their respective zone or longitudinal region in parallel, etc., in order to ensure that lamination heads **134** in longitudinal region **123** are not operated in close proximity to lamination heads **134** in longitudinal region **123-1** during layup.

[0051] In one embodiment, the controller **174** places splice zones **190**, **123-5** at the overlap zones **191**, **123-2** discussed above with regard to step **206**. In one embodiment, the controller **174** places the splice zones **190**, **123-5** in accordance with an NC program designed for the specific part at locations specified by a designer of the composite part **55**, **55-1**. The splice zones **190**, **123-5** enable structural strength to be carried from one zone to a neighboring zone in a manner similar to a portion without a splice zone **190**, **123-5**. The splice zones **190**, **123-5** facilitate zone one **115**, zone two **117**, zone three **117-1** and longitudinal region **123**, **123-1** to be defined instead of one large lamination zone with no splices. The number of lamination zone one **115**, zone two **117**, zone three **117-1** and longitudinal region **123**, **123-1** increases the rate of material being laid down. Thus, in one embodiment if each half-barrel fuselage is zonally laminated by three material layup zones, the rate of material placement can be increased by up to six-fold over a full barrel section that utilizes but one material placement device.

[0052] In step **208**, tows **124**, **124-1** of unidirectional fiber reinforced material for the laminate **120** are applied/laid-up over a layup mandrel **110** at the same time via the lamination heads **134**, such that each lamination head **134** applies the tows **124**, **124-1** in a zone one **115**, zone two **117**, zone three **117-1** and longitudinal region **123**, **123-1**. Thus, layup is applied either directly onto the layup mandrel **110** in a first layer ply **396** or is applied for a subsequent ply **398** atop the first layer ply **396**. That is, controller **174** operates the lamination heads **134** concurrently and in synchronization, in accordance one or more stored NC programs to lay up tows **124**, **124-1** for the laminate **120**. During these operations, the lamination heads **134** precisely position the tows **124**, **124-1** in order to ensure that gaps **125** and overlaps **125-1** between edges and starts and stops do not exceed desired tolerances. While tows **124** proceeding in the process direction **180** are shown in FIG. **1**B, tows **124** are placed such that their fiber orientations (e.g., 0°, +45°, −45°,) 90° vary with respect to the laminate **120**, depending on the layer being laid-up. The lamination heads **134** are also capable of motion lateral **134-1** relative to the track **132**, to facilitate motion for the placement of 0° tows, and/or arcuate motion **134-2** relative to the track **132** for the placement of 45° tows. The layup process may be completed at a single lamination station **130** or may be performed in part by multiple lamination stations **130**, **130-1**, **130-***n* placed in series with respect to the process direction **180**. In many instances, the multiple lamination stations **130**, **130-1**, **130-***n* process is desirable, as different portions of a fuselage **12** or wing **15**, **16** of an aircraft may exhibit vastly different thicknesses owing to pad-ups. For example, a pad-up for a window or door surround, or at the wing root, or an access door, or a pad-up for an antenna may be substantially thicker than other regions of the laminate **120**.

[0053] In step **210**, the controller **174** operates the lamination heads **134** to splice the zones together while applying the tows **124**. That is, at the same time with step **208**, the lamination heads **134** splice the zones together during the laying up of the zones. This is done in order to form a single, integral laminate. Any suitable splice or joint may be prepared, such as a scarf joint (not shown), lap splice **392-1**, step overlap (not shown), etc., and the overlap **399-1** sufficient to ensure high bond strength, such as a ramp rate 30:1 or higher ratio of overlap **399-1** to ply thickness may also be chosen. Furthermore, a “splice” may comprise angled butt **385**, **386** or non-angled butt **387**, **387-1** configuration, overlapping **399**, **399-1**, or otherwise stacking layers of zone one **115**, zone two **117** and zone three **117-1** and longitudinal region **123**, **123-1** against each other. This may be performed as a separate process, or may be integrated into step **208**, such that tows **124**, **124-1** from each of zone one **115**, zone two **117** and zone three **117-1** and longitudinal region **123**, **123-1** are extended into splice zones **190**, **123-5** by a desired overlap **399**, **399-1** amount or ramp rate, in order to form a splice between zone one **115**, zone two **117** and zone three **117-1** and longitudinal region **123**, **123-1**.

[0054] In one embodiment, applying tows **124**, **124-1** of fiber reinforced material to the layup mandrel **110** is performed simultaneously via lamination heads **134** at lamination stations **130**, **130-1**, wherein each of the lamination heads **134** applies tows **124**, **124-1** in an assigned zone at the layup mandrel **110**, and lamination heads **134** at different lamination station **130**, **130-1**, **130-***n* apply tows **124**, **124-1** in different assigned zones and or regions. The steps of moving the layup mandrel **110**, indexing the layup mandrel **110**, and applying tows **124**, **124-1** are then iteratively repeated. In such an embodiment, each lamination head **134** is assigned to the zone one **115**, zone two **117** and zone three **117-1** and longitudinal region **123**, **123-1** while applying tows **124**, and the zone assigned to each lamination head **134** varies as the layup mandrel **110** proceeds in the process direction **180**.

[0055] The process may further continue by moving the layup mandrel **110** further in the process direction **180**, and applying additional tows **124**, **124-1** of fiber reinforced material to the layup mandrel **110** simultaneously via the lamination heads **134** such that each lamination head **134** applies tows in a different zone. In still further embodiments, this may include moving the layup mandrel **110** further in the process direction **180**, indexing the layup mandrel **110** to the lamination heads **134**, and applying additional tows **124**, **124-1** of fiber reinforced material to the layup mandrel **110** simultaneously via the lamination heads **134**, wherein each of the lamination heads **134** applies tows in a new zone one of zones Z**1**-Z**3** of FIG. **3**A. Neighboring zones zone one **115**, zone two **117** and zone three **117-1** and longitudinal region **123**, **123-1** are then structurally united via the use of splice zones **190**, **123-5**).

[0056] The completed laminate **120** is compacted, and proceeds into the autoclave **193**. At the autoclave **193**, the laminate **120** is hardened onto the layup mandrel **110** in step **212** to form a composite part **55**, **55-1**. The composite part **55**, **55-1** is then demolded, machined, and assembled with other parts to form an aircraft **10**.

[0057] Method **200** provides a technical benefit over prior techniques and systems, because it enables lamination throughput to be multiplicatively enhanced. Because more lamination heads **134** operate at once on the laminate **120** for composite parts **55**, **55-1** contemplated the laminate **120** for a twenty-five to forty-foot long half-barrel section preform **24-1**, or a laminate **509** for a wing panel **510** of FIG. **5**, the layup time for these parts is reduced. Wing panel **510** corresponds to wing panel **30** after hardening and post hardening assembly. Furthermore, because the parts proceed along the fabrication environment **100**, transportation time adds little to non-value added time.
[0058] FIG. **2**B is a flowchart illustrating a method **250** for selecting splice locations at a laminate in an illustrative embodiment. Step **252** includes subdividing a design for a laminate into zones for lamination heads **134** (e.g., zone Z**2**A, Z**2**B, Z**2**C, Z**3**A, Z**3**B, Z**3**C of FIG. **3**B), such that different zones receive layup from different lamination heads **134**. Step **254** comprises identifying contiguous regions (e.g., contiguous regions **377** of FIG. **3**B) within the laminate that have a ply count less than an average ply count within the laminate. In step **256**, a controller places splices zones **190**, **123-5** into the design between the zones (e.g., zone Z**2**A, Z**2**B, Z**2**C, Z**3**A, Z**3**B, Z**3**C of FIG. **3**B) within the contiguous regions. In step **258**, the laminate **120** is laid-up according to the design. Method **250** provides a technical benefit by reducing layup complexity. That is, the addition of splice zones **190**, **123-5** does not substantially increase the complexity of the existing layup, nor does the addition of splice zones **190**, **123-5** increase the complexity of regions that are already highly complex (e.g., regions near windows, doors, etc.).
[0059] FIG. **2**C depicts another method **260** for selecting splice locations at a laminate in an illustrative embodiment. Step **262** comprises cutting an applied tow **124**, **124-1** to a length to facilitate splice zones **190**, **123-5** between the zone one **115**, zone two **117** and zone three **117-1** and longitudinal region **123**, **123-1** assigned to different lamination heads **134** in a design for a laminate **120**, **509**. In one embodiment, the layup splice **392** is formed from a combination of angled butts **385**, **386** that are staggered at overlaps **399**, **399-1** across plies **396**, **398**, **397** (as shown in FIG. **2**E, **2**F, 2G, **2**H). Step **264** comprises identifying a neighboring ply **398**. A neighboring ply **398** comprises an adjacent ply in the laminate **120**, **509**. Step **266** comprises overlapping **399**, **399-1** a trim position for the neighboring ply **398** from the prior ply **396** length layup splice **392**. In an embodiment, overlapping **399** a tow **124**, **124-1** may comprise changing an angle of the tow **124**, **124-1** trim, or offsetting the layup splice **392** for ply **396** from layup splice **394** for adjacent ply **398**.
[0060] FIG. **2**D is a flowchart illustrating a method **270** for staggering layup splices **392**, **394**, **395** in an illustrative embodiment, and is described with reference to FIG. **2**E. FIG. **2**E, **2**G corresponds with view arrows **2**E and **2**G of FIG. **1**B. Step **272** includes inserting a layup splice **392** into a ply **396** at a splice zone **190** between the zone one **115**, zone two **117** and zone three **117-1** assigned to different lamination heads **134** in a design for a laminate **120**, and step **274** includes identifying a neighboring ply **398** that is adjacent to ply **396** of the laminate **120**. Step **276** includes offsetting a cut position of layup splice **394** for the neighboring ply **398** from the trimmed length of ply **396**. This may be performed by overlapping **399** the layup splice **394** by a predetermined amount. A layup splice **392** within splice zone **190** refers to layup splice **392** within ply **396** within longitudinal region **123**, **123-1** and zone one **115** and zone two **117** laid up with different lamination heads **134**. The layup splice **394** for a ply **398** is staggered with respect to a subsequent layup splice **395** in ply **397** and prior ply **396** layup splice **392** within splice zone **190**. In FIG. **2**G, the lap splice **392-1** within splice zone **123-5** refers to splice **392-1** within ply **396-1** within longitudinal region **123**, **123-1** and zone one **115** and zone two **117** laid up with different lamination heads **134**. The layup splice **394-1** for a ply **398-1** is staggered with respect to a subsequent layup splice **395-1** in ply **397-1** and prior ply **396-1** lap splice **392-1** within splice zone **123-5**. Steps **272-276** may be repeated for plies until layup splice **392**, **394**, **395** proceed through the entire laminate **120** at overlaps **399**. In one embodiment, the splice zone **123-5** is formed from a combination of layup splices **392**, **394**, **395**, and are staggered across plies **396**, **398**, **397**. Method

270 provides a technical benefit by distributing plies **396**, **398**, **397** across splice zone **123-5** at overlaps **399**.
[0061] In further embodiments, the method includes operating multiple lamination heads **134** that place material on zone two **117** and zone three **117-1** of the laminate **120**, while operating a single lamination head **134** for placing material on the zone one **115** of the laminate **120**. In a still further embodiment, the method includes selecting an amount of overlap **399**, **399-1** between different plies **396**, **398**, **397** of the layup splice **392**, **394**, **395**.
[0062] In yet another embodiment, the method further includes selecting an amount of stagger between cuts in different layers of the splice. In some embodiments, the splice zones **190**, **123-5** have layup splices **392**, **394**, **395**, staggered by overlaps **399**, **399-1** from adjacent plies from plies **396**, to ply **398** to ply **397** and so on through laminate **120**. In this arrangement, tows **124**, **124-1** of individual plies within splice zones **190**, **123-5**, such as ply segment **393** are terminated at layup splice **392** with an angled butt **385**, **386** and a non-angled butt **387**, **387-1** configuration as part of a lap splice **392-1** with no separation or a small separation (e.g., a fraction of an inch) from ply segment **393-1** at layup splice **392**. The layup splice **392** has ply segment **393** and ply segment **393-1** cut and placed into a complementary angled butt **385**, **386** and a non-angled butt **387**, **387-1** configuration as part of a lap splice **392-1** with overlaps **399**, **399-1** staggering in relation to the layup splice **394**. This type of overlaps **399**, **399-1** staggering of subsequent layup splices **392**, **394**, **395** provides the lap splicing **392-1** that facilitates load transfer through splice zones **190**, **123-5**. Another embodiment has the splice in a scarf or step lap configuration (not shown). All splice types require the ply segment **393** and ply segment **393-1** to be trimmed into complementary alignment. Ply **396** has a layup splice **392** staggered from the ply **398** layup splice **394** and so forth for each subsequent ply of laminate **120**. Furthermore, splice zones **190**, **123-5** are located in less complex or thinner portions of the laminate **120**, such as areas without window/door surrounds, pad ups or other complicated geometries. In this manner, splices are positioned between complex layup areas instead of within those areas. A splice may be thicker than the thickness of an un-spliced laminate **120**, and hence the splice may comprise staggered joins of one or more cuts portions of ply through the thickness of the laminate **120**. In further embodiments, the locations of cuts for individual plies **396**, **398**, **397** within a layup splice **392**, **394**, **395** are staggered relative to angled butt **385**, **386** and non-angled butt **387**, **387-1** for other plies in the splice zone **190**, **123-5**. This causes the layup splice **392**, **394**, **395** to be staggered across a distance of a multiple of overlap **399**, **399-1**, which enhances load bearing properties of the lap splice **392-1**. Staggering the positions of cuts of plies within a splice zone **190**, **123-5** enhances the ability of the splice zone **190**, **123-5** to bear load there through when hardened into a composite part **55**, **55-1**. After receiving layup, the layup mandrel **110** proceeds to an autoclave **193**.
[0063] FIG. **2**F depicts angled butts **385**, **385-1**, **386** overlapped **399-1** between zones in an illustrative embodiment. As shown in FIG. **2**F, a first zone **381** and a second zone **382** include an upper ply **383**, **383-1** and a lower ply **384**, **384-1**. An angled butt **385** at the upper plies **383**, **383-1** is disposed at the overlap **399-1** from an angled butt **386** for the lower plies **384**, **384-1**. Angled butt **385**, **385-1**, **386** are at angle **386-2** of 45 degrees as illustrated. In other embodiments, the angle **386-2** of angled butt **385**, **385-1**, **386** is set at any angle between about 20 and 90 degrees as long as the angled butt **385**, **385-1**, **386** are set to maintain a minimum overlap **399-1**. The **385**, **385-1** FIG. **2**G depicts overlapping non-angled butts **387**, **387-1**, **387-2** between zones in an illustrative embodiment. As shown in FIG. **2**H, a first zone **381** and a second zone **382** include an upper ply **383**, **383-1** and a lower ply **384**, **384-1**. The non-angled butt **387** at the upper plies **383**, **383-1** is disposed at the overlap **399** from an angled butt **387-1** for the lower plies **384**, **384-1**.
[0064] FIG. **3**B is a side view of the half barrel section **24-2** from the same view angle as FIG. **1**B on FIG. **3**A, but after separation from layup mandrel **110**. Half barrel section **24** corresponds to half barrel section **24-2** except post hardening assembly has proceeded to completion.
[0065] In FIG. **3**B, zones are separated both radially and longitudinally, resulting in zones Z**2**A,

Z2B, and Z2C, which are disposed over zones Z3A, Z3B, and Z3C. Contiguous regions **377** have a ply count lower than an average ply count through the laminate. Zones Z3A, Z3B, and Z3C include a pad-up **372** for a window belt where window cut-out region **378** will be placed. However, the pad-up **372** is interrupted by window cut-out region **378** where material will be cut from the laminate **320**, corresponds to laminate **120**, to enable installation of a window. Zone Z3C includes a pad-up **374** for a door and a door cut-out region **375** for a door to be installed into. Meanwhile, zone Z2A includes a pad-up **376** for a crown module. Further and more complex arrangements of plies within each zone may be implemented during design as desired. Longitudinal splices **379**, correspond to splice zone **190**, are placed between the zones in the contiguous regions **377** and proceed in a longitudinal direction L. Longitudinal splices **379** have a predetermined width, although they are shown as lines in FIG. 3B. Furthermore, circumferential splices **373**, correspond to splice zone **123-5** are placed between the zones, and proceed in a circumferential direction C around the laminate **320**.

[0066] That is, after each micro pulse or pulse, the lamination heads **134** switch their direction of operation from counterclockwise to clockwise or vice versa. Thus, all of the lamination heads **134** work counterclockwise, then wait for a micro pulse or pulse, then work clockwise, then wait for a micro pulse or pulse, and so on. This may be performed without any type of “carriage return” or return from a counterclockwise trip placing tow **124**, **124-1** to a clockwise return trip during a single micro pulse and pause sequence. To place tows **124**, **124-1** of different fiber orientations, a combination of movement of the track **132**, the layup mandrel **110**, and/or the lamination heads **134** may be performed.

[0067] In another embodiment, the lamination heads **134** perform layup in the clockwise direction **64** until reaching the end of their radial zone (e.g., Z1, Z2, Z3), and then reset counterclockwise **65** back to the beginning of their radial zone (e.g., Z1, Z2, Z3) in a manner similar to operating a carriage return of a typewriter. Thus, the lamination heads **134** all work clockwise **64** after a micro pulse or pulse, then return to their starting positions and work clockwise (CW) again after a next pulse. Similar operations may of course be performed for counterclockwise **65** operation instead of clockwise **64**. In still further embodiments, plies (e.g., plies **126**, plies **128** of FIG. 1B) are laid-up longitudinally (along dimension L) by motion of the track **132**, the lamination heads **134**, or the pulsed motion (P) of the layup mandrel **110** underneath.

[0068] In still further embodiments, after the structure (i.e., layup mandrel **110**) has been pulsed (P), the lamination heads **134** move incrementally in one direction (e.g., clockwise **64**, counterclockwise **65**), and perform layup during these movements, as they each proceed across their zones (Z1, Z2, Z3). Then the lamination heads **134** move in an opposite direction back to a starting point **338** during a micro pulse or pulse/pause cycle in order to prepare for additional layup. The layup mandrel **110** may then be pulsed to a next lamination station **130**, and the lamination heads proceed to place lamination material in a counterclockwise direction **65**.

[0069] In yet further embodiments wherein the layup mandrel **110** is continuously moved in the process direction **180** (e.g., at a rate of an inch per minute), a combination of movement of the track **132**, the layup mandrel **110**, and/or the lamination heads **134** may be performed in order for layup to be performed onto the moving mandrel.

[0070] While zone one **115**, zone two **117**, and zone three **117-1**, of roughly sixty-degrees each, are depicted in FIG. 3A, as are splices **190** and splices **123-5**, which structurally unite the zone one **115**, zone two **117**, and zone three **117-1**. Any suitable number of zone one **115**, zone two **117**, and zone three **117-1** may be chosen, and the number and size of zone one **115**, zone two **117**, and zone three **117-1** may vary along the length **181-7** of the layup mandrel **110** or with respect to each other in the same lengthwise portion **318** of the layup mandrel **110**. Still further, in some embodiments certain zone one **115**, zone two **117**, and zone three **117-1** may be skipped by certain lamination stations **130**. For example, one lamination station **130** may perform layup in zone two **117** and zone three **117-1** but not in zone one **115**, while a downstream **181-2** lamination station **130** may perform layup in zone one **115**, zone two **117**, and zone three **117-1**. This may accommodate environments where zone two **117** and zone three **117-1** have more plies than Z2 in the laminate. In still further embodiments, the layup mandrel **110** may be designed for a full barrel section **29-1**, **29-2**, **29-3**, **29-4**, **29-5**, a quarter-barrel section of fuselage, or any suitable arcuate portion of fuselage. In further embodiments, zonal sizes **317** are selected such that each zone takes a similar (or the same) amount of time to layup at each lamination station **130**. This facilitates a common takt time for each lamination station **130** facilitating a more even division of work between lamination stations **130**. In such embodiments, zones with more plies, or zones that require more complex layup patterns, are made smaller than zones which are thinner or less complex.

[0071] In an embodiment, during lamination station **130** or lamination head **134** down time lamination heads **134** are eligible for servicing such as by re-loading the lamination heads **134** with new tows, replacing or cleaning cutters at the lamination heads **134**, replacing entire lamination heads, etc. Servicing could be a factor in dividing work load and creating the common takt for the line with scheduled down time for lamination stations **130** or lamination heads **134** made a part of the process to create laminate **120** or laminate **509**. In such embodiments, an amount of material laid-up in each zone is chosen to be less than a maximum rate of the lamination head **134** servicing the zone with the remaining down time left for servicing. In this manner, the lamination head **134** may be serviced during any associated down-time when layup is not occurring.

[0072] FIG. **4**A is a top view of a ply map **400** for a laminate **120** after placement of all tows **124**, **124-1** in an embodiment as illustrated. FIG. **4**A corresponds with view arrows **4** of FIG. **3**A. According to FIG. **4**A, ply map **400** includes zones A, which are utilized by a first lamination station **130**, as well as zones B, which are utilized by a second lamination station **130-1**. Splices **410** between the zone one **115**, zone two **117**, and zone three **117-1** vary along the length **181-7** of the ply map **400**, forming a staggered pattern **430** and preventing a single seam from being formed along the length **181-7** of the ply map **400**. Overlap zone **191** occurs between zone one **115** and zone two **117** and between zone one **115** and zone three **117-1**. While either first lamination station **130** and second lamination station **130-1** can form splices between zones A and zone B, the ply map **400** has the ply segment **393** placed by lamination station **130** and ply segment **393-1** placed by lamination station **130-1** for layup splice **392**. That is, zonal lamination is performed such that boundaries **412** between zones are staggered across layers in order to avoid layup splice **392** in laminate **120** or laminate **509**. In further embodiments, zones A and B overlap in angled shapes depending on the fiber orientation of material being laid-up and a local configuration of the structure being laid up.

[0073] Each splice **410** may be worked upon by multiple lamination heads **134** dedicated to a particular zone one **115**, zone two **117**, and zone three **117-1**. For example, portions of a splice **410** located between two zones **431-1** may receive layup from two lamination heads **134** (one for each zone one **115** and zone two **117** or zone one **115** and zone three **117-1**)) at different times. The portions of a splice **410** at a corner **431** between four zones **431-2** may receive layup from four lamination heads **134** (one for each zone one **115**, zone two **117** and zone three **117-1**) at different times. While the splices **410** are shown as lines, each splice **410** occupies a splice zone **190**, **123-5** between neighboring zones where plies from the zones are spliced, or otherwise made physically integral with each other. That is, the location of a splice **410** changes incrementally between layers, forming a staggered pattern **430** (e.g., stair step pattern, staggered shape, etc.) through laminate **120**. The staggered pattern **430** of splice **410** prevents overlap splice **392-2** from stacking directly upon prior lap splice **392-1** or subsequent overlap splice **392-3** and also helps to prevent an undesired thickening of the laminate **120** within splice zone **190**. Thus, the location of the layup splice **392**, **394**, **395** for splice **410** vary between plies in one embodiment. The splices **410** extend across a thickness of laminate **120**. The splices **410** are selected/placed such that they do not intersect the pad-ups **420**, in order to prevent substantial increases in thickness or complexity near pad-ups **420**. Thus, the boundaries **412** are staggered from ply **396** to ply **398** to form staggered pattern **430** for each ply **396**, **398**, **397**.

[0074] FIG. **4**B illustrates a similar arrangement of zones A and B, as well as splices **410** of a ply map **450** for a wing panel. Pad-ups **420** are also included in the ply map **450**, and may be utilized to provide reinforcement for access panels, rib lands, spar lands, etc. FIGS. **4**A-**4**B illustrate that the zonal lamination techniques discussed herein can be utilized for a variety of laminate designs. FIG. **4**B is a top view of a ply map **450** for a laminate **509** after placement of all tows **124**, **124-1** in an embodiment that corresponds to wing panel **30** prior to hardening. According to FIG. **4**B, ply map **450** includes zones A, which are utilized by a first lamination station **130**, as well as zones B, which are utilized by a second lamination station **130-1**. Splices **410-1** between the zone one **115-1**, zone two **117-2**, and zone three **117-3** vary along the length **181-8** of the ply map **450**, forming a staggered pattern **430-1** and preventing a single seam from being formed along the length **181-8** of the ply map **450**. Overlap zone **191** occurs between zone one **115-1** and zone two **117-2** and between zone one **115-1** and zone three **117-3**. While either first lamination station **130** and second lamination station **130-1** can form splices between zones A and zone B, the ply map **450** has the ply segment **393** placed by lamination station **130** and ply segment **393-1** placed by lamination station **130-1** for layup splice **392**. That is, zonal lamination is performed such that boundaries **412-1** between zones are staggered across layers in order to avoid layup splice **392** in laminate **509**. In further embodiments, zones A and B overlap in angled shapes depending on the fiber orientation of material being laid-up and a local configuration of the structure being laid up.

[0075] Each splice **410-1** may be worked upon by multiple lamination heads **134** dedicated to a particular zone one **115-1**, zone two **117-2**, and zone three **117-3**. For example, portions of a splice **410-1** located between two zones **431-7** may receive layup from two lamination heads **134** (one for each zone one **115-1** and zone two **117-2** or zone one **115-1** and zone three **117-3**) at different times. The portions of a splice **410-1** at a corner **431-9** between four zones **431-8** may receive layup from four lamination heads **134** (one for each zone one **115-1**, zone two **117-2** and zone three **117-3**) at different times. While the splices **410-1** are shown as lines, each splice **410-1** occupies splice zones **190**, **123-5** between neighboring zones where plies from the zones are spliced, or otherwise made physically integral with each other. That is, the location of a splice **410-1** changes incrementally between layers, forming a staggered pattern **430-1** (e.g., stair step pattern, staggered shape, etc.) through laminate **509**. The staggered pattern **430-1** of splice **410-1** prevents overlap splice **392-2** from stacking directly upon prior lap splice **392-1** or subsequent overlap splice **392-3** and also helps to prevent an undesired thickening of the laminate **509** within splice zone **190**. Thus, the location of the layup splice **392**, **394**, **395** for splice **410-1** vary between plies in one embodiment. The splices **410-1** extend across a thickness of laminate **509**. The splices **410-1** are selected/placed such that they do not intersect the pad-ups **420**, in order to prevent substantial increases in thickness or complexity near pad-ups **420**. Thus, the boundaries **412** are staggered from ply **396** to ply **398** to form staggered pattern **430-1** for each ply **396**, **398**, **397**.

[0076] FIGS. **5-6** are perspective views of a fabrication environment for laying up wing skins (e.g., wing panels **510** and **610**) in an illustrative embodiment. Wing panel **510**, **610** corresponds to wing panel **30** after hardening and post hardening assembly. According to FIG. **5**, a wing panel **510** is subdivided into zones **117-3**, **115-1**, **117-2** from fore to aft in a fabrication environment **500**. Lamination heads **522** at lamination stations **520** proceed along tracks **524** to perform layup in these zones **117-3**, **115-1**, **117-2**. Splices **540** are placed between the zones **117-3**, **115-1**, **117-2**. In further embodiments, lamination heads **522** at different lamination stations **520** operate at different portions of the wing panel **510** at the same time. For example, lamination heads **134** at different stations may perform layup at different zones, like zone **117-3**, **115-1**, **117-2**. In this embodiment, lamination heads **522** are staggered between different lamination stations **520**, such that lamination heads **522** at each lamination station **520** do not perform work upon adjacent zones **117-3**, **115-1**, **117-2**, but rather perform work on every other zone **117-3**, **115-1**, **117-2**.

[0077] According to FIG. **6**, a wing panel **610** is subdivided into zones Z**1**, Z**2**, Z**3** from outboard to inboard in a fabrication environment **600**. Lamination heads **622** at lamination stations **620** proceed along tracks **624** to perform layup in these zones. The zones Z**1**, Z**2**, Z**3** are made physically integral with each other via splices **640**. Within each splice **640**, plies from different zones overlap in a staggered manner. In further embodiments, more than three zones are implemented for each wing. Still further, zones Z**1**, Z**2**, Z**3** may be separated in a combination of fore/aft (as shown in FIG. **5**) and inboard/outboard (as shown in FIG. **6**) delineations in a checkerboard pattern, and multiple lamination heads **522**, **622** disposed across multiple lamination stations **520**, **620** may operate on the wing panel **510**, **610** as the wing panel **510**, **610** proceeds in the process direction **180-1**, **180-2** in order to increase fabrication rates. For example, each lamination station **520**, **620** depicted in FIGS. **5-6** may include a lamination head **522**, **622**, and tracks **524**, **624** for the lamination heads **522**, **622** may be substantially flat or otherwise dimensioned to accommodate passage of the wing panel **510**, **610**. In further embodiments, lamination heads **522**, **622** at different lamination stations **520**, **620** operate at different portions of the wing panel **510**, **610** at the same time. For example, lamination heads **622** at different lamination stations **620** perform layup at different zones Z**1**, Z**2**, Z**3**. In this embodiment, lamination heads **622** are staggered between different lamination stations **620**, such that lamination heads **622** at each lamination station **620** do not perform work upon adjacent zones Z**1**, Z**2**, Z**3**, but rather perform work on every other zone Z**1**, Z**2**, Z**3**.

EXAMPLES

[0078] Referring more particularly to the drawings, embodiments of the disclosure may be described in the context of aircraft manufacturing and service in method **700** as shown in FIG. **7** and an aircraft **702** as shown in FIG. **8**. During pre-production, method **700** may include specification and design **704** of the aircraft **702** and material procurement **706**. During production, component and subassembly manufacturing **708** and system integration **710** of the aircraft **702** takes place. Thereafter, the aircraft **702** may go through certification and delivery **712** in order to be placed in service **714**. While in service by a customer, the aircraft **702** is scheduled for routine work in maintenance and service **716** (which may also include modification, reconfiguration, refurbishment, and so on). Apparatus and methods embodied herein may be employed during any one or more suitable stages of the production and service described in method **700** (e.g., specification and design **704**, material procurement **706**, component and subassembly manufacturing **708**, system integration **710**, certification and delivery **712**, in service **714**, maintenance and service **716**) and/or any suitable component of aircraft **702** (e.g., airframe **718**, systems **720**, interior **722**, propulsion system **724**, electrical system **726**, hydraulic system **728**, environmental system **730**).

[0079] Each of the processes of method **700** may be performed or carried out by a system integrator, a third party, and/or an operator (e.g., a customer). For the purposes of this description, a system integrator may include without limitation any number of aircraft manufacturers and major-system subcontractors; a third party may include without limitation any number of vendors, subcontractors, and suppliers; and an operator may be an airline, leasing company, military entity, service organization, and so on.

[0080] As shown in FIG. **8**, the aircraft **702** produced by method **700** may include an airframe **718** with a plurality of systems **720** and an interior **722**. Examples of systems **720** include one or more of a propulsion system **724**, an electrical system **726**, a hydraulic system **728**, and an environmental system **730**. Any number of other systems may be included. Although an aerospace example is shown, the principles of the invention may be applied to other industries, such as the automotive industry.

[0081] As already mentioned above, apparatus and methods embodied herein may be employed during any one or more of the stages of the production and service described in method **700**. For example, components or subassemblies corresponding to component and subassembly manufacturing **708** may be fabricated or manufactured in a manner similar to components or subassemblies produced while the aircraft **702** is in service. Also, one or more apparatus embodiments, method embodiments, or a combination thereof may be utilized during the subassembly manufacturing **708** and system integration **710**, for example, by substantially expediting assembly of or reducing the cost of an aircraft **702**. Similarly, one or more of apparatus embodiments, method embodiments, or a combination thereof may be utilized while the aircraft **702** is in service, for example and without limitation during the maintenance and service **716**. Thus, the invention may be used in any stages discussed herein, or any combination thereof, such as specification and design **704**, material procurement **706**, component and subassembly manufacturing **708**, system integration **710**, certification and delivery **712**, in service **714**, maintenance and service **716**) and/or any suitable component of aircraft **702** (e.g., airframe **718**, systems **720**, interior **722**, propulsion system **724**, electrical system **726**, hydraulic system **728**, and/or environmental system **730**.

[0082] In one embodiment, a part comprises a portion of airframe **718**, and is manufactured during component and subassembly manufacturing **708**. The part may then be assembled into an aircraft in system integration **710**, and then be utilized in service **714** until wear renders the part unusable. Then, in maintenance and service **716**, the part may be discarded and replaced with a newly manufactured part. Inventive components and methods may be utilized throughout component and subassembly manufacturing **708** in order to manufacture new parts.

[0083] Any of the various control elements (e.g., electrical or electronic components) shown in the figures or described herein may be implemented as hardware, a processor implementing software, a processor implementing firmware, or some combination of these. For example, an element may be implemented as dedicated hardware. Dedicated hardware elements may be referred to as “processors”, “controllers”, or some similar terminology. When provided by a processor, the functions may be provided by a single dedicated processor, by a single shared processor, or by a plurality of individual processors, some of which may be shared. Moreover, explicit use of the term “processor” or “controller” should not be construed to refer exclusively to hardware capable of executing software, and may implicitly include, without limitation, digital signal processor (DSP) hardware, a network processor, application specific integrated circuit (ASIC) or other circuitry, field programmable gate array (FPGA), read only memory (ROM) for storing software, random access memory (RAM), non-volatile storage, logic, or some other physical hardware component or module.

[0084] Also, a control element may be implemented as instructions executable by a processor or a computer to perform the functions of the element. Some examples of instructions are software, program code, and firmware. The instructions are operational when executed by the processor to direct the processor to perform the functions of the element. The instructions may be stored on storage devices that are readable by the processor. Some examples of the storage devices are digital or solid-state memories, magnetic storage media such as a magnetic disks and magnetic tapes, hard drives, or optically readable digital data storage media.

[0085] Although specific embodiments are described herein, the scope of the disclosure is not limited to those specific embodiments. The scope of the disclosure is defined by the following claims and any equivalents thereof.

Claims

1. An apparatus for fabricating a composite part, the apparatus comprising: a lamination station that enables lamination heads to follow a contour of a layup mandrel that moves in a process direction during fabrication of a composite part; and lamination heads disposed at the lamination station configured to lay up tows of fiber reinforced material onto the layup mandrel, the lamination heads being configured to operate in tandem to lay up fiber-reinforced material for a laminate in different zones at the layup mandrel while splicing the zones together.

2. The apparatus of claim 1, wherein: the layup mandrel defines a contour for a section of fuselage; and the apparatus further comprises a controller that subdivides the laminate into zones by assigning lamination heads to zones that comprise arcuate portions of the section of fuselage, based on instructions in a Numerical Control (NC) program.
3. The apparatus of claim 1, wherein: the layup mandrel defines a contour for a wing panel; and the apparatus further comprises a controller that subdivides the laminate into zones by assigning lamination heads to zones proceeding from a tip of the wing panel to a root of the wing panel, based on instructions in a Numerical Control (NC) program.
4. The apparatus of claim 1, wherein: the layup mandrel defines an Outer Mold Line (OML) of a wing.
5. The apparatus of claim 1, wherein: the layup mandrel defines an Inner Mold Line (IML) of a section of fuselage.
6. The apparatus of claim 1, wherein: the layup mandrel defines a contour for a wing panel; and the apparatus further comprises a controller that subdivides the laminate into zones by assigning lamination heads to zones proceeding from a fore of the wing panel to an aft of the wing panel, based on instructions in a Numerical Control (NC) program.
7. The apparatus of claim 1, further comprising: a controller that identifies regions at the laminate which will receive pad-ups, and subdivides the laminate into zones, wherein the controller places boundaries between the zones in locations that do not intersect pad ups at the laminate.
8. The apparatus of claim 1, further comprising: a controller that subdivides the laminate into zones, and places boundaries between the zones in a staggered pattern.
9. The apparatus of claim 1, further comprising: a lamination head that is disposed downstream of the lamination heads and that performs re-work on the laminate.
10. The apparatus of claim 1, wherein: the lamination heads simultaneously lay up the fiber-reinforced material and splice the zones together.
11. The apparatus of claim 1, wherein: the lamination heads splice the zones together by cutting through applied tows and offsetting cut positions for neighboring plies of the cut applied tows.
12. The apparatus of claim 1, wherein: the lamination heads splice the zones together by trimming plies from the zones into complementary alignment.
13. The apparatus of claim 1, wherein multiple lamination heads are disposed along a shared track.
14. The apparatus of claim 13, wherein the shared track is complementary to the contour of the layup mandrel.
15. The apparatus of claim 1, wherein multiple lamination heads are each disposed along a respective individual track.
16. The apparatus of claim 15, wherein each respective individual track is offset a different offset from the layup mandrel.
17. A system for fabricating a composite part, the system comprising: a track that follows a contour of a layup mandrel that moves in a process direction during fabrication of a composite part; and a lamination station that comprises: lamination heads that are movably mounted to the track and are configured to lay up fiber reinforced material onto the layup mandrel, the lamination heads being configured to operate in tandem to simultaneously lay up fiber-reinforced material for a laminate in different zones at the layup mandrel while simultaneously splicing the zones together.
18. The system of claim 17, wherein: the layup mandrel defines an Outer Mold Line (OML) of a wing.
19. The system of claim 17, wherein: the layup mandrel defines an Inner Mold Line (IML) of a section of fuselage.
20. An apparatus for fabricating a composite part, the apparatus comprising: a lamination station that enables lamination heads to follow a contour of a layup mandrel that moves in a process direction during fabrication of a composite part, wherein the layup mandrel defines an Inner Mold Line (IML) of a section of fuselage or an Outer Mold Line (OML) of a wing panel; lamination

heads disposed at the lamination station configured to lay up tows of fiber reinforced material onto the layup mandrel, the lamination heads being configured to operate in tandem to simultaneously lay up fiber-reinforced material for a laminate in different zones at the layup mandrel while splicing the zones together; a controller that identifies regions at the laminate which will receive pad-ups and subdivides the laminate into zones by assigning lamination heads to zones that comprise arcuate portions of the section of fuselage, proceed from a tip of the wing panel to a root of the wing panel, or proceed from a fore of the wing panel to an aft of the wing panel, based on instructions in a Numerical Control (NC) program, wherein the controller places boundaries between the zones in a staggered pattern in locations that do not intersect pad ups at the laminate; and a lamination head that is disposed downstream of the lamination heads and that performs re-work on the laminate.