A method for fabricating composite structures at a low-cost, moderate-to-high production rate. A first embodiment of the method includes employing a continuous press forming fabrication process. A second embodiment of the method includes employing a pultrusion process for obtaining composite structures. The methods include coating yarns with matrix material, weaving the yarn into fabric to produce a continuous fabric supply and feeding multiple layers of net-shaped fabrics having optimally oriented fibers into a debulking tool to form an undebulked preform. The continuous press forming fabrication process includes partially debulking the preform, cutting the partially debulked preform and debulking the partially debulked preform to form a net-shape. An electron-beam or similar technique then cures the structure. The pultrusion fabric process includes feeding the undebulked preform into a heated die and gradually debulking the undebulked preform. The undebulked preform in the heated die changes dimension until a desired cross-sectional dimension is achieved. This process further includes obtaining a net-shaped infiltrated uncured preform, cutting the uncured preform to a desired length and electron-beam curing (or similar technique) the uncured preform. These fabrication methods produce superior structures formed at higher production rates, resulting in lower cost and high structural performance.

4 Claims, 2 Drawing Sheets
The debulking process includes closing a heated partial debulking tool 24 onto the undebulked preform 22. This compresses the fabric and reduces the void content of the part. The debulking process is usually inexpensive because of the low temperature and pressure requirements.

After the debulked preform 22 is partially debulked, it is drawn out of the partial debulking tool 24 and cut from the continuous supply of fabric 20 to form a partially debulked preform 26. The partially debulked preform 26 is placed into one of many net-shaped debulking tools 28 where the preform 26 is debulked to net-shape. Sufficient heat and pressure are applied to the partially debulked preform 26 so that the matrix material in the fabric 20 melts and flows. The flow of the matrix material facilitates the debulking process so that the partially debulked preform 26 can be formed to net shape and the matrix material is uniformly and continuously dispersed within the preform 26. Heat is then removed from the process allowing the matrix material to solidify. The time required in the net-shaped debulking process is dependent on the type of matrix material employed. Processing time is on the order of five to ten times longer than the initial partial debulking operation. Because of the difference in times between the partial debulking and the net-shaped debulking operations a single partial debulking tool 24 can feed multiple net-shaped debulking tools 28.

Once the matrix material has completely solidified, an uncured structural part 30 can be removed from the debulking tool 28 without deforming. That is, the uncured structural part 30 retains its shape without support from the debulking tool 28.

The net-shaped debulking tools 28 are subject to moderate pressures and temperatures during the debulking to net-shape process. However, the debulking tools 28 are inexpensive relative to those used in conventional autoclave processes. After the uncured structural part 30 has been debulked to netshape and removed from the debulking tool 28, it is placed into an electron-beam chamber 32 where it is cured and is output as a cured structure 34. The uncured structural part 30 is free-standing. That is, no tooling is required for the uncured structural part 30 to maintain its shape during the electron-beam curing process. The amount of time required to cure the uncured structural part 30 employing an electron-beam is a function of part size, thickness and complexity. Cure times are on the order of, for example, approximately seconds to several minutes as compared to multiple hours for typical autoclave cures. The electron-beam curing process eliminates the time and costs associated with autoclave cure. Furthermore, the heat curing of matrix material can create chemical reactions that result in the formation of undesirable voids and anomalies in the interior of the composite structure. If the voids or anomalies are large enough, then the structural performance of the part suffers and the structure may not be serviceable. The use of an electron-beam as in the preferred embodiment of the present invention does not cause chemical reactions that can result in the formation of voids. Furthermore, electron-beam curing of matrix material can be performed at any desired temperature which virtually eliminates residual thermal stresses. Electron-beam curing also allows the curing of asymmetric laminates without causing significant warpage caused by residual thermal stresses.
An all heat cure can also be employed in the aforementioned fabrication process, but the advantages will not be as great as using an electron-beam cure. In addition, the continuous supply of net-shaped fabric facilitates the automated continuous process for the fabrication of the composite structure. The use of coated yarns allows the use of high performance damage tolerant matrix material and particle toughening technology to produce damage tolerant structures. The fabrication process is compatible with moderate to high volume production rate applications unlike autoclave processes. Tooling for both the partial preform debulking and the debulking to net-shape is relatively inexpensive.

In lieu of using a matrix material that is a priori coated on the structural fibers a resin injection process, such as resin transfer molding, can be used to infiltrate a resin (matrix material) into the preform 26. The process of forming composite primary structures using these types of resins is identical to the process in the above-mentioned first embodiment of the method of the present invention except that during the net-shaped debulking process, the resin is injected into the debulking tool 28 displacing all remaining air within the tool cavity. Depending upon the formulation of the resin, the resin may solidify as the heat is reduced allowing the structure to go through an electron-beam cure in a free standing condition. If the resin remains a liquid at ambient conditions, then the entire tool must be exposed to an electron-beam while the part is cured. In this latter processing technique, the part cannot be removed from the debulking tool 28 until it is cured. This latter processing technique is the least efficient of the three techniques described. It is obvious to those having ordinary skill in the art that alternative resin formulations can be developed and applied to this forming process where the resin can be totally or partially cured by heat or UV light prior to final curing with an electron-beam.

According to a second embodiment of the method of the present invention as shown in FIG. 2, a pultrusion fabrication process is employed. The pultrusion fabrication process is similar to conventional pultrusion processes except it depends upon the utilization of a continuous supply of fabric as described in U.S. Pat. No. 5,394,906. Final curing of the structure is performed by electron-beam. As with the continuous press forming fabrication process mentioned above with respect to the first embodiment of the method of the present invention, the process of the second embodiment includes coating structural yarns, which form the fabric 20 with matrix material. As above with respect to the first embodiment, this eliminates the need for infiltrating matrix material into the preform because it is already integral to the fabric. The method then includes feeding multiple layers of fabric 20 together forming an unbekulked preform 22.

The unbekulked preform 22 is fed into a heated die 40. The unbekulked preform 22 gradually changes dimensions until it has been totally debulked and desired cross-sectional dimensions have been obtained. However, this preform 22 is pulled through the heated die 40, matrix material flows and the preform gradually compresses to the final dimensions of the heated die 40. FIG. 2, is shown as an I-beam 42. As the preform traverses the constant cross-sectional portion of the heated die 40, heat is removed and the matrix material solidifies. The length of the constant cross-sectional shape of the heated die 40 is a function of the melting temperature of the matrix material and the pultrusion rate.

Once the structure is pultruded through the heated die 40, it is an uncured structure. However, it no longer requires the use of the heated die 40 to maintain its shape. After a desired length of the structure, for example, a beam 42, has been pultruded, it is cut without interruption of the pultrusion process. The uncured beam 42 which has been cut to length is then input to an electron-beam chamber 32 for curing. The final product is a cured structure 44 having a desired shape and length. Because the preferred embodiment of the present invention employs a method using a continuous net-shaped fabric having optimally tailored fiber orientations and an electron-beam 32 for curing, this results in a superior structure obtained faster and at a lower cost than conventional pultrusion processes.

It should be noted that the final shape of a structure in the pultrusion process can be any desired shape and is not limited to the I-beam shown in FIG. 2. Provided the geometry of the cross section is constant along its length. The pultrusion process of the preferred embodiments of the present invention is approximately 10 to 100 times faster than conventional pultrusion processes depending upon matrix material formulation and part geometry.

The foregoing is considered as illustrative only of the principles of the invention. Further, since numerous modifications and changes will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and applications shown and described, and accordingly, all suitable modifications and equivalents may be resorted to, falling within the scope of the invention and the appended claims and their equivalents.

That is, the pultrusion process is not restricted to using matrix material (resin) coated fabrics. For example, an alternative pultrusion process draws the fabric through a resin bath prior to the fabric entering an unheated die. A further alternate pultrusion process injects the matrix material into the preform through the die wall. If the resin is not formulated to solidify in the die, then an electron-beam must be integrated into the die to cure the structure as it is being pultruded. If the resin is formulated to solidify in the die, then the process continues as originally described. Resins can be formulated to cure by heat and UV light in combination with electron-beams in a manner similar to the above-described compression forming process. The aforementioned pultrusion process can be readily modified by one of skill in the art to accommodate these as well as other modifications.

What is claimed is:

1. A method for fabricating composite structures having non-uniform shapes, said method comprising the steps of:
   (a) coating structural yarns with matrix material;
   (b) weaving fabric from the structural yarns into a net-shaped structure having optimal fiber orientations into a continuous supply of fabric, so that one net-shaped structure is successively attached to another;
   (c) drawing multiple layers of a first series of fabric through rollers and guides;
   (d) assembling the layers of the first series of fabric into an unbekulked preform;
   (e) partially debulking the preform using a partial debulking tool;
   (f) drawing the partially debulked preform from the debulking tool and advancing a next series of fabric into the partial debulking tool;
   (g) cutting the partially debulked preform from the continuous supply of fabric, so that the successively attached net-shaped structures are separated;
   (h) feeding the partially debulked preform to multiple net-shaped debulking tools;
(i) debulking the partially debulked preform to net-shape and solidifying the matrix material by removing heat from the process while the net-shaped infiltrated preform is in the net-shaped debulking tools; and
(j) curing the matrix material.

2. A method according to claim 1, wherein said step (j) includes curing using one of an electron-beam, ultraviolet beam, heat and a combination of any of these.

3. A method according to claim 1, wherein in said step (e) the preform is partially debulked using a heated partial debulking tool.

4. A method for fabricating composite structures having non-uniform shapes, said method comprising the steps of:
(a) weaving fabric from the structural yarns into a net-shaped structure having optimal fiber orientations into a continuous supply of fabric, so that one net-shaped structure is successively attached to another;
(b) drawing multiple layers of a first series of fabric through rollers and guide;
(c) assembling the layers of the first series of fabric into an undebulk preform;
(d) partially debulking the preform using a partial debulking tool;
(e) drawing the partially debulked preform from the debulking tool and advancing a next series of fabric into the partial debulking tool;
(f) cutting the partially debulked preform from the continuous supply of fabric, so that the successively attached net-shaped structures are separated;
(g) feeding the partially debulked preform to multiple net-shaped debulking tools;
(h) debulking the partially debulked preform to net-shape while uniformly and continuously infiltrating the matrix material into the preform, and solidifying the matrix material by removing heat from the process while the net-shaped infiltrated preform is in the net-shaped debulking tools; and
(i) curing the matrix material.

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