

Optimum Design of Composite Structures: A Literature Survey (1969–2009)

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Abstract

Optimum structural design of composites is a research subject that has drawn the attention of many researchers for more than 40 years with a growing interest. In this study, a review of the literature on this subject is presented. The papers are classified according to the type of the composite structure optimized in those studies, the loading conditions, the objective function, the structural analysis method, the design variables, the constraints, the failure criteria, and the search algorithm used by the researchers.

Keywords

Composites, design optimization, objective function, design variables, constraints, search algorithms

Introduction

Composite materials are widely used in the industry because of their superior mechanical, thermal, and chemical properties, e.g. high stiffness-to-weight and strength-to-weight ratios, corrosive resistance, low thermal expansion, vibration damping. As a further advantage, composite materials offer a great flexibility in design, allowing change of the material system in many ways. Configurations of a laminate, i.e. fiber orientation, ply thickness, material of each ply, stacking sequence, type and volume fraction of reinforcement can be tailored to make a better use of material or attain a desired property like strength, elastic modulus, thermal and electrical conductivity, thermal expansion coefficient. One may thus significantly decrease the weight of a structure by optimizing the design of the composite material itself, or increase its performance using the same amount of material. However, the traditional approach of designing by trial and error, which heavily relies on designer's experience and intuition, promises little success with a huge number of design variables. For that reason, development of optimization methodologies incorporating structural analysis methods and search algorithms is necessary. Accordingly, optimum design of

composites drew the attention of many researchers.^{1–1007}

In many of these studies, plain fiber-reinforced laminated composite plates were considered for optimization; besides, others types of composite structures were optimized: Structures reinforced with short or long fibers,^{6,70,113,300,545,618,696,899,958} particulate fillers,^{352,425,737,821} braided or woven fibers,^{291,326,336,347,425,530,531,710,880,884,923,1006} or carbon nanotubes,⁹⁹³ laminates with layers having variable fiber orientation,^{149,173,219,243,247,271,311,325,355,359,446,564,633,709,720,730,732,771,787,796,797,814,831,877,885,900,906,910,951–954} or variable fiber density,^{325,472,900} variable-thickness laminates,^{5,42,52,87,95,123,156,160,166,173,200,209,217,219,232,247,276,282,283,318,355,383,412,413,442,457,470,482,498,540,593,605,647,655,661,683,771,792,845,851,906,911,913,921,990} laminated plates with holes^{12,54,68,78,112,130,131,143,150,160,164,171,232,242,248,281,296,297,298,313,316,}

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- 354,379,380,381,412,413,416,428,450,468,474,477,486,505,519,669,670,
683,696,521,547,574,707,709,710,733,771,774,779,787,800,855,906,909,
911,915,935,936,951,959 or cracks,^{299,602,604} perforated
plates,^{503,667,827} composite plates reinforced by shape
memory alloy fibers,^{307,928} arbitrary-shaped plates,^{173,}
313,447,490,547,611,634,651,683,730,828,846,953,962 hybrid lami-
nates, which have layers made of different materi-
als,^{21,102,112,137,138,141,152,153,181,182,189,202,210,218,220,230,}
256,268,324,326,334,352,374,383,388,423,478,479,491,515,596,616,624,
639,642,660,695,697,711,714,725–727,759,761,791,821–824,833,839,859,
862,882,933,940,946,974,975,981,983,984 armors,^{189,479,624,695,754,}
862,946 laminates containing viscoelastic damping
layers,^{117,386,569,980} laminates with weak interfaces,⁸⁴⁴
sandwich plates, which contain a core between two
sheets with high stiffness,^{9,10,25,47,51,81,82,90,93,94,98,115,}
116,120,128,175,176,218,240,267,292,321,372,410,432,452,459,465,482,
496,542,543,546,557,562,578,583,599,606,620,621,628,640,652,657,671,
674,677,688,729,766,829,834,882,888,900,904,907,924,925,944,960,961,
969,970,1004,1007 multi-material composite structures,
which are composed of various materials at different
locations,^{151,260,348,378,429,463,482,484,499,503,514,548,720,744,}
776,786,839,884,886,939,966,968,976,982 stiffened plates,^{47,73,99,}
100,123,171,217,220,248,257,272,296,322,328,353,362,363,375,394,419,
448,496,511,527,537,543,565,566,587,604,605,607,608,621,646,674,691,
693,694,713,742,743,766,775,794,802,832,836,838,867,868,877,896,897,
898,901,905,912,930–932,947,956,970 structures with reinforcing
elements, or patches, bonded on their surfaces,^{168,492,}
553,574,598,779,813,875,876,882,893,916 laminates with uncer-
tainty in geometry, fiber orientation, or material prop-
erties,^{15,136,151,187,195,197,212,225,228,233,305,308,322,344,347,385,}
408,411,501,509,516,520,522,637,685,716,738–740,762,771,802,807,809,
817,843,869,887,895,902,903,911,934,943,955,978,988,989 composite
shell structures,^{16,57,71,77,146,159,163,169,199,212,236,237,253,}
261,293,294,304,305,327,329,361,369,370,373,417,418,437,449,494,498,
506,516,536,550,573,579,593,595,615,627,636,664,675,690,664,720,731,
732,755,764,783,803,810,815,816,819,859,870,872,874,885,891,938,941,
976 variable thickness shells,^{167,705,706} shells with vari-
able fiber orientation,^{705,706} shells with a hole,^{289,361,}
449 sandwich shells,^{167,199,253,544,765,825,884,894} hybrid
shells,^{390,391,398,745,926,942} stiffened shells,^{53,92,199,204,213,}
236,367,405,476,500,518,520,527,563,616,653,686,728,745,768,769,790,
908 pressure vessels,^{20,23,44,55,110,209,293,343,391,431,456,483,}
491,507,558,588,591,609,628,637,649,734,788,799,865,871,973,983,984,
1000 pipes, tubes, cylinders,^{30,37,72,119,134,154,172,190,222,237,}
244,250,266,301,304,312,331,347,389,390,403,420,426,434,473,501,506,
513,522,525,526,535,570,585,592,636,647,663,685,689,692,736,746,777,
801,808,849,914,929,943,945,997,999,1005 cylinders with
holes,^{190,332} hybrid cylinders,^{340,444,500,983,984} sandwich
cylinders,^{30,88,122,144,330,847,889} stiffened cylinders,^{7,30,}
235–237,404,703,971 sandwich structures having variable
thickness,^{25,122,127,128,145} composite beams,^{48,52,76,86,106,}
127,146,147,207,258,274,288,294,310,348,360,376,383,406,410,422,423,
433,440,441,481,529,554,568,580,581,622,639,648,726,733,773,839,846,
857,883,913,918,958,968 stiffened beams,⁸⁴⁸ box-beams,^{96,105,}
148,178,275,326,409,568,841,852,864,918 curved beams,^{179,339,345,648}
variable thickness beams,^{89,200,227,384,839} sandwich
beams,^{1,3,15,18,43,62,66,89,97,107,127,145,178,179,205,400,513,601,}
603,643,687,698,781,848,977,992 columns,^{43,856} aircraft wings,^{8,}
12,28,33,36,42,47,111,126,131,143,165,166,186,217,368,439,442,455,487,
623,708,716,741,758,826,835,840,843,880,916 wing boxes,^{47,104,123,}
205,423,451,495,679,811,818,835,861,913 aircraft tail,⁸⁹³ rotating
blades,^{253,333,625} turbine blades,^{223,324} wind turbine
blades,^{346,712,720,965} rotor blades,^{241,262,279,314,356,436,668,}
719,722 propellers,^{625,676,677,972} shafts,^{52,87,276,580,581,767,}
789 robot arms or manipulators,^{96,147,148,273,274,308}
leaf springs,^{464,552,641,858} helical springs,^{530,1006} tennis
rackets,²¹¹ flywheels,^{32,75,124,403,444,510,532,579,746,831,954}
wrenches,⁵²³ connecting rods,⁷³³ links,⁷³³ fuselage,^{222,}
453,414,544,657,894 satellite parts,^{321,820,882} train bodies,
car bodies,^{717,822,825,884} car wheel,²³⁸ motorcycle
frames,⁸⁸² ship hulls,⁶²¹ submarine structures,^{728,860,955}
sails,⁹¹⁰ silo structures,^{592,593} dental bridges,⁹⁹¹ pin
joints, bolted joints,^{139,143,208,374,751,770,772,845,890} scarf
joints,^{760,949,1003} lap joints,^{63,484,786} snap joints,³⁸²
joints for tubular structures,^{619,759} press fit joints,⁷⁶⁷
brackets,^{892,965} grid or lattice structures,^{309,870} fiber-
reinforced structures with complex shapes,^{71,395,402,414,}
482,551,671,684,773,820,846,964 3D composite structures,^{180,}
662,991 composite structures with embedded circuit
boards,⁹¹³ shells,^{750,985–987} plates,^{290,357,364,407,427,439,445,}
466,469,485,524,571,590,613,638,644,694,780,806,822,830,853,854,986
sandwich structures,^{306,571} or beams^{275,320,358,471,480,485,}
656,793,812 with piezoelectric actuators or sensors. The
skins of the sandwich structures considered in the
design optimization studies were mostly fiber-rein-
forced polymer in order to obtain high stiffness and
strength, but some were metals^{15,25,93,330,400,546,583,765,}
825,888,992,1004,1007 or plastics,²⁶⁷ while the cores were
cellular like honeycomb and rectangular,^{30,43,51,81,82,88,}
90,115,122,240,321,372,459,465,496,543,544,571,583,578,620,729,781,829,
834,847,848,882,884,888,894,924,925,977,1004 corrugated,^{175,199,}
546,847,848 grid,^{175,199} tapered hexagonal forms,¹²⁰
foam,^{93,107,111,126,176,253,267,292,306,330,452,482,551,562,601,603,}
621,628,643,652,657,671,687,698,765,766,825,848,884,900,907,960,961,
969,970,992,1004 metal foam,¹⁰⁰⁷ viscoelastic materials like
rubber,^{400,944,1004} plastics,⁶⁰⁶ cork,¹⁰⁰⁴ resin-concrete,⁷⁶⁶
wood,^{606,1004} plywood,¹⁰⁰⁴ mineral wool,¹⁰⁰⁴ cera-
mic,⁵⁵⁷ truss,^{834,847} or metal box.^{178,205,674} In most of
the studies, fiber-reinforced polymer–matrix composites
were considered. In some studies, ceramic-matrix,^{70,253,}
377,426,684,816 concrete-matrix,⁹⁶⁸ or metal-matrix^{300,331,}
341,377,545,882 composites, and functionally graded com-
posites^{341,737,781,821,872,960,961} were optimized.
- The structures considered by the researchers were
under various types of loading conditions. The
researchers optimizing composite plates or shells
usually considered in-plane loads, transverse loads,
and bending and/or twisting moments. In some studies,
some other types of loading were also considered like
axial loading of plates through bolts,^{143,208,296,374,751,845,}

⁸⁹⁰ axial loading of joints,^{484,786} torsional loading,^{7,23,52,63,72,119,209,222,389,434,456,525,526,550,627,649,663,849,926} bending,^{88,513,570} lateral loading,^{943,945} axial loading,^{7,23,30,88,110,119,134,144,154,172,209,222,235–237,244,266,301,312,330,332,347,373,389,390,404,434,473,506,507,522,525–527,535,550,616,619,627,649,663,685,686,692,703,777,808,849,926,929,945,971,999} outer or inner pressure^{7,20,23,37,44,55,88,110,119,134,144,159,190,209,235,236,237,250,266,289,293,312,330–332,340,343,347,391,398,420,431,456,483,491,501,507,522,525,526,535,558,591,592,609,619,628,636,637,663,734,736,750,759,788,799,801,847,849,865,871,914,926,971,973,983,984,1000} on pressure vessels, pipes, or cylinders, torsional loads,^{87,275,276,348,409,580,581,767,773,846} transverse loads, bending moments,^{1,3,18,48,76,96,105,107,117,127,147,200,227,258,275,308,310,320,339,345,376,400,406,409,410,422,441,464,481,523,529,552,554,568,622,643,648,726,732,733,776,781,818,821,839,857,858,913,918,968} and axial loads^{43,179,207,409,433,529,554,581,776} on beams, multiple independent load cases,^{1,17,35,36,60,64,92,108,136,157,218,220,247,265,286,309,344,355,360,412,413,442,496,538,544,586,622,623,717,730,753,797,882,894,913} random loads,^{136,151,197,228,233,265,267,347,371,410,525,526,577,610,661,685,716,802,843,943,955} vibrational excitation or cyclic loads,^{69,86,97,140,146,306,334,376,512,618,779,822,894} dynamic loading,^{89,200,274,275,638,644,737,806,945,952} impact loading,^{203,307,533,624,641,675,725,737,754,791,802,838,884,900,928,937,956} ballistic impact loading,^{189,479,624,695,754,802,862,946} blast loading,^{546,763,961,993,1007} fluid pressure or contact pressure,^{131,167,358,544,593,621,657,684,705,706,733,894,955,972} aerodynamic loading,^{8,33,36,42,111,126,186,205,217,241,262,279,314,333,346,356,368,436,439,442,451,455,487,544,565,623,668,672,708,712,716,719,722,741,795,835,840,880,884,893,913} loads causing plastic deformation,⁴⁷⁶ thermal loads,^{71,80,131,138,253,309,321,341,392,397,426,443,461,475,477,496,504,508,509,521,527,532,539,556,557,575,584,586,600,637,642,654,661,665,684,689,701,727,735,736,744,784,795,801,817,821,859,866,872,882,913,933,939,992,996,997} hygrothermal loads,^{91,174,409,539,614,882,952} erosive thermo-fluid loading,³⁵² friction,^{592,593} centrifugal forces,^{403,444,532,831,954} weight,^{96,105,167,367,622,684,882} inertial loads,^{37,42,75,96,105,124,241,274,308,324,455,459,510,579,623,625,656,736,746,831,882,954} electrical voltage applied to piezoelectric actuators.^{290,306,364,427,445,469,471,480,485,571,638,694,806,822,853,854}

The purpose of optimization is to find the best design for a composite structure according to a chosen criterion under various constraints imposed by the requirements of the design. The optimum design provides either the most efficient and effective use of material or the best performance. The problem is to find the design resulting in the minimum value for an undesired feature or response of the structure or the maximum value for a desired feature. Accordingly, in some of the studies, the goal was to minimize laminate thickness,^{12,17,35,38,59,60,64,83,84,110,129,136,143,155,157,165,170,174,188,191,206,211,225,234,253,254,259,265,267,268,282,286,293,315,317,319,333,343–345,350,351,360,379,380,387,396,408,410,411,415,428,438,498,501,505,535,539,541,592,595,617,622,627,632,637,640,650,713,724,739,748,749,753,762,803,807,809,817,833,840,887,895,903,913,915,}

^{917,948,974} weight (other than pure thickness minimization of the laminate),^{1,3,7–10,15,16,18,25,28–30,33,36,41–43,47,51,53,62,64,66,73,76,81,87,88,90,92,93,95,98,104,107,111,112,120,123,126–128,131,143–145,151,156,166,171,176,183,192,205,207–209,213,217,218,220,222,227,238,240,241,248,256,258,261,269,272,276,292,309,321,322,325,328,355,368,375,377,384,388,390,394,404,405,412–414,422,423,437,442,447,451–453,455,457,459,464,467–470,476,479,482,487,490,491,495,497,503,511–513,518,520,529,540,543,544,546,547,552,562,563,565,566,568,574,578,581,582,593,599,604,605,611,616,619–621,623,628,633,639,641,648,651,652,655,657,670,671,679,685–688,703,705–707,715,725,726,728,733,741,743,754,759,761,763,768,769,771,775,790,793,802,808,811,812,818,825,835,836,839,840,847,848,858,860,861,868,870,871,878,882,884,894,896,897,901,906,907,911–913,921,922,925,926,931,932,947,955,956,958,962,969,970,973,981,977,1004} density,^{291,424,425,923} fiber volume fraction,¹¹ material and/or manufacturing cost,^{182,194,230,324,326,388,400,419,453,513,515,564,606,674,725,898,926,953,974,975} maximum stress or strain,^{312,398,432,647,991} nonuniformity in stress,^{37,54,636,760} stress concentration,^{63,95,214,242,300,354,426,657,760,774,827,846,951} stress levels in critical regions,^{779,916} difference in the strengths of different regions of a structure,³² stress intensity factor,^{299,492} residual stress,³⁰⁰ free edge stresses,^{185,277,556} interlaminar normal stress,⁹⁵⁰ bearing stress in the joint,⁸⁹⁰ thermal stresses,²⁵³ thermal distortions,^{321,341,596,642} thermal conductivity,⁶⁵⁴ thermal expansion,³⁷⁸ strain energy,^{44,416,596,720,923} variation of strain energy around a hole,²⁸⁹ the extent of plastic zone,⁴⁷⁶ dynamic deflection response,^{89,146,148,290,306,307,445,575,576,615,644,656,664,722,822,928,952,985–987} dynamic loads,⁶⁶⁸ natural frequency,⁹⁵² permanent deflection or depth of penetration due to impact,^{624,937} impact induced delamination damage,⁹⁰⁰ fatigue damage,⁵¹² post buckling delamination damage,⁸³² variation in the response of laminates due to uncertainty in fiber angles,⁵¹⁶ variation in resultant stiffness properties due to uncertainty in the properties of constituent materials,⁹⁸⁸ maximum deflection,^{49,146,240,306,351,362,542,614,694,696,875,893,937} twist angle,^{625,719} shear-normal stress coupling,⁶⁶⁷ acoustic transmission,^{585,698,829,834,889} the difference between the mechanical responses of structures with or without hole,³³² the difference between the current and target reliabilities³⁴⁷ or natural frequencies,^{100,957} the difference between the calculated and measured displacements,⁷⁰⁴ the difference between the target and calculated deformed shapes or deflections,^{383,469,571,793,853,854,966} the difference between the target and calculated curvatures induced by residual stresses,⁵⁸⁴ or the difference between current and target values of material properties like elastic modulus, Poisson's ratio, stiffness components, thermal conductivity, density, thermal expansion coefficient.^{56,195,300,336,385,424,425,431,462,465,493,531,545,757,805,852,939,982,1002} In some other studies, the objective was to maximize the static strength of composite laminates for a given thickness or weight,^{4,6,20–23,45,46,48,55,58,68,71,78,79,91,101,109,121,130,150,184,197,198,223,252,}

295,297,298,313,335,338,342,365,374,402,456,458,475,481,488,499,501, 513,519,534,538,548,549,558,570,598,609,612,629,649,669,683,684,696, 697,707,709,756,757,767,772,781,798,801,821,841–843,851,865,877,923, 934,953,964,965,978 or for a given volume,⁵ or to maximize specific strength,¹¹⁵ strength-to-weight ratio,^{114,115,184, 601,643} buckling strength,^{2,21,22,26,27,39,40,57,74,77,102,118, 119,133,134,137,141,154,158–160,163,172,175,179,187,188,190,198,199, 202,204,210,215,216,224,226,229,235–237,239,246,248–250,255,264,266, 268,271,278,281,294,301,304,318,327,337,340,342,353,366,370,372,373, 380,385,389,391,406,420,434,443,450,461,473,474,477,494,495,497,506– 509,521,525–527,541,547,550,555,559,573,575,577,587,591,608,610,613, 617,626,631,640,646,653,661,663,678,680,681,690,691,700,702,706,718, 721,727,735,738,740,755,794,837,844,849,856,857,863,865,867,869,881, 891,901,904,908,909,914,918,929,930,936,967,971,976,990,994,1001}

post buckling strength,⁵⁸⁷ interlaminar strength,^{659,785,792,960} delamination strength,^{583,589} fiber–matrix interface strength,²²¹ fracture toughness,^{602,635} fracture energy,⁷⁰ strength of joints,^{139,382,484,751,767,786,845,949, 1003} burst pressure of pressure vessels,^{209,799} internal-volume-to-weight ratio of pressure vessels,¹⁰⁰⁰ creep rupture strength,³³¹ compressive stress in the ceramic core,⁵⁵⁷ stiffness,^{48,67,72,79,80,85,86,102,132,147,149,161,164,169, 173,177,180,184,192,193,195,219,228,229,232,247,257,270,274,282,284, 296,300,311,348,349,351,359,367,395,397,401,402,410,421,429,431,446, 463,472,477,483,486,489,502,513,521,523,528,541,551,553,554,567,634, 658,666,677,680,683,699,716,720,730,732,733,737,747,748,750,756,757, 764,766,770,773,776,781,796,797,800,810,813,820,846,883,888,900,902, 910,925,941,953,1001} stiffness-to-weight ratio,¹⁸⁴ residual stiffness after microstructural fracture,⁹²⁷ impact resistance,²⁰³ blast resistance,^{961,993} minimum penetrating ballistic velocity,^{189,695,754,862,946} energy absorption capacity,^{45,132,244,339,777,838,873,961,989} strain energy density,⁹⁶⁸ energy storage capacity of flywheels,^{75,124,403, 444,510,532,579,746,831,954} damping,^{86,96,97,105,106,113,117,148, 168,251,285,288,320,334,376,386,407,514,569,638,722,766,806,944} fatigue strength,^{69,779} fatigue life,⁷⁷² buckling temperature,^{138,392,461,504,933,996,997} thermal conductivity,⁶⁵⁴ thermal expansion along a specific direction,³⁷⁸ heat insulation capacity,³⁵² cooling rate,⁷⁴⁴ sound transmission loss,⁶⁰³ flutter speed limit,^{672,708,758,835,880} aerodynamic performance,^{126,186,253,279,314,436,555,795} bending-twisting or extension-twisting coupling,^{409,784} curvature induced during manufacturing,⁷¹¹ effectiveness of propellers,^{625,676,677,972} natural frequency,^{31,49, 52,57,59,61,99,102,103,125,153,169,181,224,243,245,263,273,285,293,294, 302,316,329,350,361,369,379–381,393,399,417,418,428,440,449,460,467, 469,477,500,505,515,517,521,524,536,572,590,597,630,693,720,723,729, 731,742,750,780,782,783,787,789,804,814,819,823,850,851,855,879,885, 893,895,899,904,935,938,957,959,995,998,1001} separation of natural frequencies,^{61,153,181,460,515,787,823,851,855,957} performance characteristics of structures with piezoelectric actuators or sensors,^{357,358,364,427,466,480,485,524,780} or reliability.^{233,371,509,522,762,809,816,887,903} Besides, multi-objective optimization problems were considered in some studies where the objective was to minimize cost

and weight,^{363,537,607,697,714,725,727,745,905,919,926,941,979,981, 983,984} cost, weight, and thickness,^{791,859,920} cost and manufacturing time,⁴¹⁹ cost and compliance,⁶⁶² weight and deflection/deformation,^{82,387,650,882,941} weight and dynamic deflection response,⁹⁴⁵ weight and strain energy,⁹⁴² weight and peak hoop stress,⁸⁷² weight and resin infiltration time,⁴⁴⁸ thickness and strain energy,²⁸³ thickness and change in the strain energy,¹⁰⁸ maximum displacement and mold filling time,⁶⁸² maximum deflection and maximum stress,³⁴⁶ deflection, rotation, and natural frequency,⁶⁰⁰ dynamic deflection response and control force,⁵⁶¹ the difference between the current and target reliabilities and the sensitivity of the structure to uncertainties in loading and material properties⁹⁴³ or to maximize static strength and buckling strength,¹⁹⁶ buckling strength and stiffness,^{196, 303, 645} buckling strength and postbuckling stiffness,²³¹ buckling strength, static strength, and stiffness,⁴⁴¹ buckling strength, critical temperature rise, and failure load,⁶⁰⁰ crippling, buckling, and post-buckling strength,⁴³³ buckling strength and fundamental frequency,^{50,560,594, 874,999} natural frequency and stiffness,⁵⁰ thermal conductivity and stiffness,⁸²⁸ thermal conductivity and bulk modulus,⁸⁸⁶ stiffness and damping,⁹⁸⁰ internal-volume-to-weight ratio and allowable internal pressure of pressure vessels.⁵⁸⁸ In some other studies of multi-objective optimization, static strength was maximized and weight or thickness was minimized,^{305,465,586,788,872} static strength was maximized and vibration, weight, and deflection were minimized,⁷¹² static strength and buckling strength were maximized and deflection was minimized,³¹⁰ buckling strength was maximized and dynamic response was minimized,^{201,665,815} buckling strength was maximized and postbuckling dynamic response was minimized,^{701,752} buckling strength and fundamental frequency were maximized and deflection was minimized,¹⁴² buckling strength was maximized and thickness was minimized,^{454,692,963} delamination strength was maximized, at the same time weight and spring-back were minimized,⁸⁹² critical shear load was maximized and thermal stresses were minimized,⁸⁶⁶ energy absorption capacity was maximized and weight was minimized,⁶⁷⁵ fundamental frequency was maximized, at the same time thermal distortions, maximum stress, maximum displacement, and weight were minimized,⁴⁹⁶ fundamental frequency was maximized and weight was minimized,^{580, 882} fundamental frequency was maximized and thermal stresses were minimized,⁶⁸⁹ fundamental frequency was maximized and dynamic response was minimized with minimum use of control energy,^{140,152,275} dynamic response was minimized with minimum use of control energy,¹⁰⁰⁵ the difference between the realized stiffness and target stiffness was minimized and torsion–bending coupling was maximized,⁸⁶⁴ weight or thickness was minimized and

stiffness was maximized,^{212,330,530,535,648,660,736,765,1006} cost was minimized and beam length was maximized,⁹⁹² cost and/or weight were minimized and stiffness was maximized,^{478,660} cost was minimized and fundamental natural frequency or separation between natural frequencies was maximized,⁸²⁴ damping and stiffness were maximized and weight was minimized,^{308,533,618} damping and stiffness were maximized, at the same time twist and acceleration were minimized,⁴³⁹ damping was maximized and weight and/or cost was minimized,^{200,944} thermal expansion coefficient was minimized and stiffness was maximized,¹⁶² axial stiffness and hoop stiffness of pressure vessels were maximized and weight was minimized,⁷⁸⁸ burst pressure and internal volume of a pressure vessel were maximized, at the same time its weight was minimized,^{55,734} effectiveness of piezoelectric actuators was maximized and mass of piezoelectric material was minimized,⁴⁷¹ sound transmission loss and stiffness were maximized, at the same time cost and stress were minimized.¹¹⁶

In composite optimization studies, usually the material system or dimensions (size) were optimized. In some studies, shape^{55,72,183,190,200,241,242,289,313,354,383,547,588,619,668–670,675,683,707,733,742,779,800,810,829,855,875,916,1000,1003} or topology^{149,219,243,247,291,325,348,358,378,427,446,447,463,466,472,490,503,514,528,547,582,596,607,651,688,730,732,744,774,776,806,826,828,846,860,882,886,888,894,925,939,966,968,976,982} of the structure was optimized. In a few studies, concurrent optimization was performed, in which the design of the part as well as its manufacturing process were optimized.^{419,448,682}

The structural response of a composite part under loading should be correctly modeled to ensure that the optimum design will actually show the expected performance. Researchers used various theories and methods to analyze composite structures. As an analytical method, many used the classical laminated plate theory, besides, some of them used von Karman plate theory,⁷⁹⁵ 3D laminated media analysis,⁵³⁴ the zig-zag plate theory,^{640,960,900,961} shear deformation theories,^{61,193,240,304,342,351,372,373,380,404,418,420,432,439,458,470,471,504,516,521,533,541,572,575,576,577,590,591,615,656,664,665,685,701,750,752,815,819,904,928,934–936,945,1005} Flügge shell theory,^{23,573,663,849} beam theories,^{1,3,76,87,111,345,406,423,433,441,481,529,552,554,621,858} or other analytical methods.^{5–7,9,18,20,21,25,30,37,43,44,70,72,75,82,86,90,92,95,97,98,104,107,110,111,115,124,144,145,170,176,178,185,187,189,202,214,223,231,235,258,267,273,276,306,307,330,331,334,336,341,352,375,384,386,400,403,405,409,444,448,479,502,513,530,532,537,546,569,589,601,603,618,621,687,695,703,746,754,758,761,765,767,785,811,821,834,847,848,852,862,864,870,874,946,977,993,1003,1004,1006,1007} As a numerical method, many researchers used finite element analysis; others used Rayleigh–Ritz method,^{22,44,53,59,67,77,79,80,125,161,163,172,186,196,229,246,263,264,270,290,302,310,393,405,421,459,460,580,581,584,594,620,681,711,714,783,803,833,877,879,897,907,969,990}

minimum potential energy principle,^{213,657} other energy methods,⁸⁴⁵ boundary element method,^{221,585,733,800,889} finite strip method,^{215,454,755} finite difference method,^{15,383} Galerkin's method,^{59,246} hybrid numerical methods.⁹⁰² The macro material properties of composite material can be obtained from constituent material properties using micromechanics.^{76,91,106,113,274,291,307,311,341,400,424,425,545,618,654,696,886,917,927,953,982,988} The optimization algorithm may be coupled with a response surface,^{71,292,382,396,414,423,495,559,602,604,605,616,624,625,635,637,645,646,672,675,677,679,685,686,690,691,705,706,708,722,743,755,769,794,817,839,849,867,868,882,891,895,924,925,928,930–932,950,971,978} Kriging,^{839,927,988} radial basis function,⁸³⁹ polynomial based approximation,^{927,988} artificial neural network models^{317,566,743,815,879,902,927} to calculate an approximate value of the objective function with a less computational burden.

In order to optimize a composite structure, some of its features affecting the objective function are allowed to be changed. The parameters defining these features are called design variables. In most of the studies, the researchers used fiber orientation angle and layer or laminate thickness as design variables. These can be either continuous or discrete. Besides other types of design variables were used like lamination parameters,^{56,77,109,110,125,142,154,158,219,228–230,245–247,263,264,270,278,302,359,446,462,493,521,531,559,572,573,614,645,646,663,672,678,679,691,699,708,729,757,794,796,810,814,836,837,840,849,851,867,868,896–898,930–932,948,957,962,1001,1002} material of the layers,^{64,117,124,218,324,374,376,379,388,390,428,467,468,478,491,500,528,551,606,628,655,660,668,697,711,725,726,766,791,808,818,882,884,907,981,1004} type of reinforcement,^{300,377,424,425} material of matrix and/or fiber,^{194,377,424,425,431,545,876,923} material properties of constituent materials like elastic modulus, Poisson's ratio, density,^{113,945,966} parameters defining the distribution of material properties,^{900,960,961} volume fraction of particulate fillers,^{352,737} fiber volume fraction,^{6,7,11,13,14,16,44,69,76,91,105,106,113,127,146,148,177,200,239,240,274,308,310,336,377,424–426,431,441,486,502,533,545,618,654,788,816,882,922,945,958,981} nano-tube volume fraction,⁹⁹³ distribution of volume fraction of fibers or one of the constituent materials,^{48,341,459,503,642,696,744,773,846,872,888,900,960} fiber shape and/or size,^{113,300,545,618,654,830,923,927,988} fiber prestress,^{556,557,636} fiber prestressing forces,³¹² interference between concentric cylinders,⁴⁰³ fiber orientation, fiber volume fraction, layer or laminate thickness, material, or density in each finite element,^{122,123,149,156,173,177,219,227,243,247,260,271,359,378,427,446,463,472,490,514,553,596,662,683,732,787,789,855,886,910,939,951,952,968,982} or segment of the structure,^{8,33,36,42,71,131,143,160,180,261,355,384,442,464,469,487,544,611,623,720,771,776,825,826,828,876,882,913} presence or nonpresence of material in a finite element,^{313,354,378,447,547,651,688,732,774,806} parameters defining the curvilinear paths of continuously placed fibers,^{311,709,751,770,796,831,877,885,900,953,954,960,961}

core density,^{32,62,107,116,603,643,652,825,848,1007} modulus of core,⁹⁹² or core thickness,^{18,25,32,43,51,62,66,81,88–90,93,107,115,116,122,144,145,218,292,330,452,578,583,603,606,620,621,652,687,765,808,825,882,889,907,969,970,977,992,1004,1007} of sandwich plates, dimensions of the cells or repeated formations in the core,^{81,90,120,122,546,583,620,847} parameters defining the shapes of the cells in the core,⁸²⁹ thickness, volume, or weight ratio of skin and core layers of sandwich structures,^{9,82,176,513,515,432,601,781,977} stiffness ratio or thickness ratio of inner and total thickness of hybrid laminates,^{21,141,152,181,182,202,478,824} the ratio of lamina thickness to total thickness of plain laminates,^{2,15,101,104,149,163,177,189,195,201,210,228,273,278,385,570,579,493,705,706,787} stiffness components or stiffness properties like elastic modulus,^{1,3,15,32,37,54,113,187,214,221,402,431,628,698,704,722,816} delamination length,⁶³⁵ geometric parameters,^{18,32,47,55,63,75,87,104,111,124,126,139,178,207,208,220,241,244,258,275,276,309,339,346,356,374,375,378,379,382,394,400,414,420,422,423,428,433,436,437,444,453,464,468,496,517,529,530,533,544,552,562,564,579,582,593,602,609,623,635,639,641,657,668,671,674,675,689,704,712,730,732,734,759,764,766,767,775–777,798,810,811,834,847,848,851,852,856–858,864,870,871,880,882,890,892,894,901,905,909,924,925,958,973,992,1006,1007} parameters defining the shape of a beam,^{383,733} a plate,⁷³³ a hole,^{130,150,183,190,232,242,289,313,332,416,547,574,669,670,707,774,855} or a reinforcement around a hole,³³² parameters defining the shape of a fillet,⁵⁴⁷ a cross-section,⁷² a pipe joint,⁶¹⁹ a scarf joint,¹⁰⁰³ or the ends of a pressure vessel,^{55,588,1000} parameters defining thickness distribution,^{5,18,25,52,75,95,167,209,217,232,282,283,318,368,470,481,482,647,661,803} parameters defining weaving pattern of fibers,^{291,923} density distribution,^{243,348,429,730,797} density or mass per unit length,⁷²² spacing, configuration, location, geometry, and/or number of stiffeners,^{7,30,47,53,92,99,100,123,171,213,222,235,248,257,272,296,322,328,353,362,363,367,368,394,404,405,419,448,476,488,511,518,520,537,543,565,566,587,605,607,616,621,653,686,693,703,728,742,743,766,768,769,790,860,868,882,896–898,901,912,931,932,942,947,956,970,971} positions of supports^{393,410} and loads,⁴¹⁰ position of mounted objects,^{368,882} position and/or orientation of holes,⁸⁰⁰ position and mass of balancing objects,⁶⁶⁸ clamping pressure of bolts,³⁷⁴ location, modulus, and size of bolts,⁸⁴⁵ scarf or lap joint angle,^{63,760,1003} location of composite patches, orientation of the fibers in the patches, number of patches, thickness, size and/or shape of patches, or patch material,^{168,492,598,813,779,875,882,893,916} angular speed of flywheels,⁵⁷⁹ volume fraction, the orientation and/or the through-thickness location of the shape memory alloy wires,^{307,928} the ratio of the perforated area to the total surface area of viscoelastic damping layers,⁹⁸⁰ thermal expansion coefficient,⁸¹⁶ location of piezoelectric actuators or sensors on a plate,^{275,290,320,364,407,439,445,471,480,485,524,613,638,644,656,750,780,822,853,854,985,987} embedding location of piezoelectric patches within the layers of composite plate,⁸²² spacing between piezoelectric actuators,³⁰⁶ thickness or

size of piezoelectric actuators,^{306,471,485,793} orientation of piezoelectric patches,^{571,822} electrical voltages applied to piezoelectric actuators,^{469,471,480,644,656,793,822,853,854,986} shape, volume fraction, and/or spatial arrangement of piezoelectric rods.^{357,358,466}

During an optimization process, the structural design may substantially be modified such that the resulting structure can no longer meet the requirements on its performance. In order to avoid unacceptable configurations, constraints are imposed on the design variables during an optimization process; e.g. a minimum stiffness is ensured by imposing an upper limit for deflections,^{1,3,12,18,25,28,34,38,42,47,49,59,84,122,123,127–129,131,143,145,146,156,165,200,222,225,227,238,240,256,258,261,265,269,272,282,283,293,315,344,351,360,403,410,412,413,419,422,423,437,469,470,476,498,500,503,520,530,552,563,565,568,583,592,595,607,615,620,632,640,641,674,665,724,726,741,745,761,765,771,793,802,812,848,858,860,861,876,884,911,913,915,923,944,965,970,977,992,1004} twist angle,^{217,741,913} curvatures,^{324,588} laminate strain components, ϵ_{xx} , ϵ_{yy} , or γ_{xy} ,^{192,226,404,491,495,637,717,727,761,836,859,897,912,922,981} strain energy,^{820,876,953} or a lower limit on extensional stiffness terms, A_{ij} ,^{17,35,113,198,317,543,554,589} transverse shear stiffness,^{113,925} torsional and/or bending stiffness,^{62,71,81,93,96,105,106,176,178,230,274,292,554,747,825} axial stiffness,^{566,947} prebuckling and/or postbuckling stiffness,⁶⁸⁶ elastic moduli,^{86,95,110,117,162,291,377,378,386,408,424,431,514,545,747,1002} stiffness coefficients,⁴²⁷ bulk modulus,³⁷⁸ or natural frequency.⁶⁰³ While minimizing thickness, weight, or cost of the structure, its strength may become too low to offer resistance to the applied loads. In such a case, a static failure criterion is used to determine the load carrying capability of the structural configuration. While maximizing stiffness, buckling strength, damping, natural frequency, etc. by modifying fiber orientations, material or thickness distribution, a static failure theory may be used^{2,5,44,75,160,176,198,219,226,228,244,247,255,266,291,321,339,353,386,439,508,580,581,621,631,719,822,831,937,951,960,961} to guard against static failure. During weight minimization of pressure vessels, a lower limit may be imposed on the burst pressure.⁹⁷³ Similarly, structural performance constraints are applied, if other failure modes are likely to be critical such as local or global buckling,^{7,30,35,42,43,47,51,53,84,87,88,90,92,104,107,108,122,123,144,150,165,166,171,178,188,198,207,208,213,222,244,248,249,254,258,265,267,268,276,277,286,321,328,344,363,375,388,390,400,404,405,415,423,437,448,495,497,511,516,518,520,530,537,546,562–566,568,578,580,581,599,605,606,616,621,627,628,639,640,652,655,672,674,679,686,703,705,706,726–728,739,743,745,752,765,769,775,795,807,808,811,836,847,859,860,861,868,870,882,884,894,896–898,901,905,911,912,926,931,932,942,945,947,948,956,962,970,974,975,983,984,1006} post-buckling strength^{566,790} or stiffness degradation,⁹⁴⁷ micro-buckling,⁶⁸⁷ crippling,⁵³⁷ wrinkling,^{107,459,578,599,652,687,992} dimpling or indentation,^{459,578,599,687} impact damage,^{675,725,956} delamination,^{191,481,725,892} fracture,^{73,604} fatigue damage,⁵¹² matrix damage,⁷²⁵

fiber damage,^{556,557} or resonance.^{16,41,49,59,61,65,66,87,99,100,127–129,146,165,182,186,192,200,241,253,256,274,276,288,292,293,308,314,315,321,333,356,368,379,384,409,428,467,468,482,500,505,515,530,568,581,623,640,652,668,698,719,726,727,771,757,763,793,803,816,829,833,882,884,889,895,911,958,970,983,984,1002} In maximizing strength, stiffness, natural frequency, reliability, or some other feature, an upper bound may be set for thickness,^{86,133,284,640,762,862,903,923,946} weight,^{99,100,137,141,149,181,321,367,429,513,580,643,720,732,748,733,813,829,834,855,862,875,890,976,944,946} cost,^{149,164,177,463,513,813,876} area,^{742,774} or volume.^{5,52,232,370,517,587,669,706,707,856,925} In maximizing energy absorption capacity, a lower limit may be imposed on strain difference between successive failure modes.⁸⁷³ Constraints may also be imposed to ensure attaining a desired property or response; e.g. specific limits may be set for the values of Poisson's ratio,^{431,757} density,^{194,431,977} thermal expansion coefficient,^{408,424,425} thermal conductivity,^{377,424–426} dynamic response,¹⁴⁸ damping,^{86,129,148,256,292,400} sound transmission loss,¹⁰⁰⁴ coefficient of moisture expansion,⁴⁰⁸ maximum temperature,^{352,872} reliability target,^{136,151,305,411,501,520,685,762,809,887,903,955} stiffness,^{86,194,982} center of mass,²⁴¹ twist angle of a wing,^{36,42,166} aerodynamic stability features like flutter, flapping,^{33,59,192,279,314,333,351,436,442,451,455,485,487,605,623,625,668,714,741,840,861,880,892} or aerodynamic performance parameters.^{111,241} Special constraints are sometimes imposed on bending stiffness terms to avoid excessive error arising due to negligence of bending-twisting coupling.^{268,303,388,559,606,645,646,738,739,807,808,940} The number of contiguous plies with the same fiber orientation may be limited to prevent matrix damage propagation and thus avoid large matrix cracks.^{198,226,248,249,254,255,286,328,335,430,473,477,494,495,508,555,559,600,612,620,645,646,659,678,679,692,716,727,731,794,795,836,842,843,852,859,861,867,868,881,883,896–898,912,926,930,932,941,963,974,983,984} An upper bound may be set to the difference between fiber angles of adjacent plies to reduce edge delaminations.^{335,473,692,842,883,963,983,984} A minimum number of plies may be required for each chosen direction to avoid domination of matrix properties in one of these directions.⁸⁸³ Manufacturing constraints may be imposed.^{71,205,363,412,413,419,423,441,448,453,540,543,632,724,734,738,775,818,822,836,865,882,885,897,912,922,981,990} To facilitate fabrication of the structure, continuity of fiber orientations between different panels or subdomains^{599,611,655,797,811,861,884,921,962} may be enforced. Upper and lower limits may be set for fiber volume fraction,^{44,48,69,76,91,105,106,113,148,149,177,200,240,274,290,307,308,336,341,426,431,528,545,618,654,696,927,968,993} particulate volume fraction,⁷³⁷ volume fraction of a constituent material.^{514,982} As in most of the studies, the laminate may be required to be symmetric to avoid bending-extension coupling. In some of the studies,^{49,50,61,84,91,132,137,138,141,153,165,181,182,193,215,216,224,297,352,450,500,584,614,654,657,711,784,805,806,811,821,826,849,882,1005}

unsymmetrical laminates were considered. In many of the studies, laminates are prescribed to be balanced to prevent shear–extension coupling. The optimized composite structure may be required to be isotropic.⁸⁸⁶ Other than behavioral constraints, side constraints may be applied; e.g. design space may be restricted to positive values of thickness and cross-sectional area^{50,51,529}; as side constraints, upper and lower limits may be set for lamina or laminate thickness^{8,18,25,36,47,50,51,53,59,61,69,74,82,84,86,92,96–100,102,105,106,108,109,120,122,123,136,140,141,144,147,157,162,181,182,192,200,202,206,217,230,231,238,240,267,274,283,285,288,292,299,305,308,318,326,330,334,340,345,359,368,411,422,426,432,452,485,506,507,535,544,567,578,595,601,603,621,628,634,637,660,671,685,698,711,714,735,743,748,754,761,801–803,809,826,839,884,887,914,969,1005} area or volume,^{96,99,100,105,190,242,243,332,416,596,598,661,683,779,806,828,886,916,924,939,954} dimensions, or geometric parameters,^{7,42,47,55,113,120,124,168,178,208,213,241,274,332,353,379,382,383,419,422,423,428,448,464,511,537,544,546,552,563,579,580,583,602,605,647,671,674,743,745,746,765,848,852,858,860,864,868,870,882,890,894,932,942,958,1000,1006} weight,^{306,348,388,478,603,606,698,789,822,876,893,974,975} mass inertia,⁶⁶⁸ density,⁵¹⁴ cost,^{388,478} control force, power, or voltage on piezoelectric materials.^{201,439,471,480,561,576,638,793,985–987}

In order to check whether a configuration generated by optimization algorithm for the composite structure will result in satisfactory performance, one should use a reliable failure criterion. As intralaminar static failure criterion, the researchers used Tsai-Wu,^{64,68,78,83,109,110,128,130,155,174,197,205,209,211,217,218,223,233,234,244,252,261,266,269,276,277,309,319,321,326,339,342,355,360,365,371,387,394,398,403,411–414,439,444,447,451,452,456,477,483,484,489,490,510,511,519,522,529,532,535,539,558,567,574,581,582,588,591,595,623,627–629,632,641,649–651,688,709,724,734,746,748,749,756,762,771,788,799,802,809,831,838,841,865,871,873,877,878,884,887,903,911,913,917,919,920,923,926,930,931,934,941,943,953,964,965,973–975,979,983,984,989,1000,1006} Tsai-Hill,^{4,12,23,44,48,55,59,73,88,91,98,111,122,127,130,131,143,147,166,170,183,196,227,252,258,259,293,295,310,313,315,319,347,354,396,423,441,457,458,475,482,483,488,498,499,511,530,538,540,549,555,566,568,586,587,599,622,629,633,648,669–671,693,697,707,715,743,748,753,756,769,774,816,842,843,861,894,906,907,921,923,944,969,978} Azzi-Tsai,^{22,47} Hoffman,^{139,206,319,345,351,368,380,482,483,485,524,541,598,613,750,835,927} Hashin,^{297,298,961,963} maximum stress criterion,^{2,8,32,38,51,53,75,76,92,124,139,156,223,225,260,272,319,343,420,437,459,491,511,556,557,565,568,592,593,605,609,612,659,684,703,713,719,746,831,838,857,878,898,917,919,920,974,975,979} maximum strain criterion,^{17,30,33,35,87,104,108,114,121,126,157,160,170,171,198,208,219,220,222,226,228,247,248,249,254,255,286,317,322,324,373,375,408,483,508,511,534,543,544,578,600,601,631,637,728,736,757,775,811,817,818,831,835,839,859,860,881,884,905,945,947,948,955,974} Hill criterion,^{21,579} quadratic failure criterion,⁶⁰ failure mode concept,⁵⁸⁴ stress interaction criterion,⁵¹¹ C2 criterion,¹⁵⁰ Ye criterion,⁹⁶⁴ Puck failure criterion,^{882,974,975} Chang-Chang failure criterion,⁹³⁷ Cheng and Lessard criterion,^{299,475} Yamada failure criterion,¹⁴³ maximum distortion energy theory,^{9,15,47,58,}

200,242,267,291,330,542,674,759,763,765,767,827,847,894,951 Huber–Mises criterion,^{563,745,942,954} Treska,⁵ maximum normal stress theory,^{761,970} critical failure volume method,⁹⁴⁹ point stress criterion,^{112,183,519} where failure criterion is checked at a specific distance for a notch, multiscale stress criteria,^{773,846} fracture mechanics,^{73,299,338} continuum damage mechanics,⁵⁰¹ energy based failure criteria,⁴³⁸ failure-mechanism based failure criteria,^{917,919,920,979} failure criteria for bolted joints,⁸⁴⁵ for delamination,^{178,481,659,725,791,832,900,961} transverse cracking,^{299,475} matrix cracking,^{725,791} or core failure of sandwich structures.^{82,90,107,145,321,546,601,628,687,847,960,961,970,992} Most of the researchers used first-ply failure approach; some of them used progressive-ply-failure approach.^{297,298,305,339,489,534,873,937,960,961,968,989}

Although composite materials offer great flexibility in product design with a large number of design variables, this feature also leads to an immense number of locally optimum designs. Finding globally optimum designs for composite structures is a difficult problem requiring sophisticated optimization procedures. A downhill proceeding algorithm monotonically decreasing the value of an objective function may get stuck into a locally optimal design other than the globally optimal one. For this reason, some researchers preferred global search algorithms like genetic algorithms,^{184,226,248,249,254,255,260,286,288,291,296,313,315,321,324,328,329,339,362,373,379,395,398,402,404,405,415,421,424,428,430,443,445,448,457,458,465,467,468,473,477,494,495,497,499–501,504,505,508,511,518,520,526,537,547–549,552,555,558,563,566,578,582,584,591,595,599,600,611,612,616,620,621,625,627,628,632,639,640,642,645,649,650,655,658,659,660,675–679,682,690,692,696,697,703,709,711–713,718,719,722,724–726,731,741,743,745,751,754,757,758,768–770,779,785,788,791,792,795,799,806,810,813,815,818,819,822–824,826,827,832,836,837,839,840,842,843,845,850–852,861,863–865,871–875,879,882–884,893–899,901,902,904,907,908,912,916,917,921–923,931,932,937,941,942,944,945,947,952–954,956,962,963,966,967,969,972,974,975,981,985,986,987,989,992,1000,1004,1006} scatter search,^{727,983} simulated annealing algorithm,^{275,317,377,425,439,524,580,581,590,597,613,640,644,700,704,746,780,858,859,878,926,984} discrete material optimization,⁹⁷⁶ improving hit-and-run,^{157,322,543,554} branch-and-bound,^{127,188,198,319,335,384,452,541,559,672,691,708,716,794,849,867,868,930} ant-colony optimization,^{747,881,940} particle swarm optimization,^{674,809,841,864,868,887,920,948,950,979,1002} tabu search,^{631,926,938,984} artificial immune system,^{315,919,973} cellular automata,^{639,730,797} evolutionary algorithms,^{354,408,490,762,774,853,854} discrete material optimization,⁷³² convex subspace single linkage method,^{553,927} mode-pursuing sampling method,⁹²⁹ random search methods.^{67,218,292,686} On the other hand, if the number of design variables is low, thus relatively few local minima exist, or an improvement is desired in the current design, or lamination parameters are used as design variables, then use of deterministic local search algorithms may be a viable

approach or use of other methods like analytical methods,^{1,3–5,9,11,13,14,19,20,37,38,43,62,70,72,75,87,95,102–104,107,110,112,115,118,124,125,132,164,176,182,185,189,197,219,227,247,267,270,306,312,331,340,345,406,440,479,481,491,503,517,561,562,575,576,592,593,629,634,664,666,695,701,752,781,803,857,870,977,1001,1003} enumeration (trial of all possible designs),^{26,27,175,179,191,199,203,204,236,237,346,376,460,483,515,519,530,550,594,610,617,646,717,756,772,777,798,830,876} design of experiments,^{382,602,635,978} heuristic or parametric studies,^{8,63,90,109,114,117,139,144,170,187,194,207,214,231,239,258,259,300,307,343,374,390,418,433,453,464,482,484,488,492,534,551,569,609,615,626,645,653,657,665,673,684,687,706,710,759,760,764,766,767,786,801,821,838,866,880,890,915,991,1007} physical programming,⁴⁷¹ or graphic based methods.^{2,4,6,21,46,56,58,60,62,68,69,102,109,121,137,141,152,153,162,168,172,181,182,195,201,202,229–231,233,235,263,264,273,302,352,385,422,502,516,545,570,608,654,694,801,842,862} Optimization with a local search may show a better promise if a multi-start optimization approach is adopted, i.e. optimization process is repeated each time starting from randomly chosen configurations.^{79,88,119,134,161,186,193,216,224,241,251,284,285,301,319,411,462,475,493,523,531,589,661,761,793,877,892,936,967} If lamination parameters are used as optimization variables, the problem becomes convex, i.e. a single local optimum point exists. In that case, using any local search algorithm becomes a feasible approach in locating the global optimum. Some researchers^{67,127,275,384,439,501,628,639,644,741,754,787,859,882,894,926,938,976,984,993} used hybrid methods, in which two or more search algorithms are used together to combine their superior features. In many of the topological optimization studies, homogenization method^{243,358,378,427,466,472,514,528,776,806,828,846,886,888,925,939,966,982} is used. In some of the studies, researchers used search algorithms specifically developed for composites optimization like layerwise optimization,^{206,447,490,586,630,681,688,723,783,837,895} in which each layer is one-by-one sequentially optimized. In some of the studies,^{192,261,269,293,429,452,495,501,563,753,775,868,871,894,912,948} multilevel approach is adopted in which one objective function is extremized after another or the same objective function is extremized using different design variables at different stages.

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