Strength of Materials, Vol. 45, No. 1, January, 2013

METHODS AND FINDINGS OF STRESS-STRAIN AND STRENGTH ANALYSES OF MULTILAYER THICK-WALLED ANISOTROPIC CYLINDERS UNDER DYNAMIC LOADING (REVIEW). PART 1. EXPERIMENTAL STUDIES

P. P. Lepikhin, V. A. Romashchenko,
and E. V. Bakhtina

UDC 539.4

The paper provides a review of the known (from available publications) methods and findings of experimental studies of stress-strain state and strength of multilayer thick-walled anisotropic cylinders under dynamic loading.

Keywords: multilayer thick-walled anisotropic cylinders, dynamic loading, stress-strain state, strength, experimental investigation methods and findings.

The development of machine building, aircraft, spacecraft and other industries has enhanced interest in dynamic processes in various structures, in particular thick-walled cylindrical shells. Among such structures are vessels, enclosures, and protective structures designed for maintaining significant hydro- and gas-dynamic loads and environmentally hazardous explosion products, including those in emergencies, at various facilities (aircraft and spacecraft, containers for storing and transporting explosive goods, toxic substances, chambers for power engineering based on explosive thermonuclear fusion, etc.). The manufacture of such structural members tends to use composite materials (CM), including those with spiral-wound layers, and metal–composite materials consisting of an internal metal layer and an external laminated composite layer.

The objective of this work is to review the known (from available publications) methods and findings of experimental investigation of stress-strain state (SSS) and strength of multilayer, primarily thick-walled, anisotropic cylinders under dynamic loading.

There have been numerous publications addressing an experimental study of composite shells' behavior under internal pulse (explosion) loading.

Ryzhanskii et al. [1] experimentally investigated the deformation and failure of water-filled cylindrical glass-reinforced epoxy (GRE) shells under internal pulse loading. The shells were made by winding T1 glass fabric pre-impregnated with IF-ÉD-6KG epoxy binder. The pulse loading of the shell was performed by blasting an explosive charge in the form of a ball of trotyl-hexogen mixture, which was placed at the shell center. The authors [1] studied the failure of geometrically similar shells with a thickness-to-outer radius ratio $\delta/R_0 = 3.7\%$ and $R_0 =$ 103.8, 155.8, and 457 mm, and shells with constant inner radius $R_0 = 100$ mm and $\delta/R_0 = 3.7$, 9.1, 16.7, and 21.3%. The time variations of outer radius and circumferential strains in the shell central section were recorded by high-speed filming and photography and strain gauging methods. Based on the measured values, researchers determined maximum radial expansion rates, strains, periods of natural radial vibrations, and maximum circumferential strain to fracture. In some experiments, an impulsive pressure was recorded by means of a manganin gauge. Presence of a through crack was taken as the shell failure criterion; it was judged by the explosion products outrush during the experiments and by external inspection afterwards. It was found out that: (i) during the explosion loading of water-filled geometrically similar GRE shells whose dimensions increased by a factor of 1.5–4.4 no scale

---

Pisarenko Institute of Problems of Strength, National Academy of Sciences of Ukraine, Kiev, Ukraine.
Translated from Problemy Prochnosti, No. 1, pp. 17 – 32, January – February, 2013. Original article submitted May 10, 2012.

effect of energy nature was observed; (ii) the shell circumferential strain prior to fracture was about 4% and was independent of wall thickness, dimensions of geometrically similar shells, and initial strain rate within the range of $(0.21\text{–}1.2)\cdot 10^3\ \mathrm{s}^{-1}$; (iii) fracture started from the outer surface in thin-walled shells and from the inner surface in thick-walled ones; (iv) GRE circumferential elastic modulus was independent of the strain rate within the range $(1.0\text{–}1.5)\cdot 10^3\ \mathrm{s}^{-1}$; (v) the material underwent elastic deformation up until fracture; (vi) the fracture was of non-shattering mode.

In [2], Tsypkin et al. studied deformation, failure, and defect-sensitivity of GRE cylindrical shells with outer radius R_0 and wall thickness δ (shell length = $4R_0$) under internal pulse loading, and compared their strength to that of steel shells under similar conditions. The experiments were carried out on cylindrical shells of GRE and steel 20 in air. Spherical explosive charges of trotyl-hexogen mixture were blasted at the shell center. GRE shells had their ends free, while the ends of steel shells were closed with heavy steel caps. GRE shells were identical in dimensions (inner radius = 116 mm and $\delta = 16$ mm) and were prepared by winding TS-8/3-T glass fabric pre-impregnated with IF-ÉD-6KG epoxy.

Dimensions of geometrically similar steel shells made of seamless pipes differed four-fold. The steel shells were subjected to single loading only, while GRE shells were loaded in a single and repeated modes. During the experiments, variation of strains in the shell central cross section was studied by photographic recording and strain gauging methods. The shell failure was identified as in [1]. Analysis [2] has shown that: (a) GRE shells deformed elastically until fracture, which is consistent with the findings [1]; (b) formation of through cracks in GRE shells under single loading was observed at circumferential strains larger or equal to 2.5%, the fracture occurring during the compression phase; (c) the shell fracture during the tension phase (in the first half-period) as in [1] occurred at strains close to 4%. Noteworthy is that during pulse loading of GRE shells [1] the dynamic compressive strains did not exceed 1% due to the presence of water in the shell. In general, the experiments [1, 2] demonstrate significant advantages of using GRE for cylindrical structures, including large-size ones, to operate under pulse loading conditions.

The paper [3] addressed the reasons that restrict load-carrying capacity of cylindrical GRE shells under single internal pulse loading. The strains and failure of open-ended shells were studied. The experimental set-up and methods of recording were detailed in [2]. Two types of shells made of fabric-based GRE similar to that in [2] were used in the experiments. The shell inner radius was 100 mm; the type I shells were 16 mm thick and 400 mm long, while type II shells had a thickness of 5 mm and length of 240 mm. The investigations revealed that the reduction of load-carrying capacity of GRE shells in air under single internal pulse loading was due to the dynamic loss of stability of radial vibrations, while the shell thickness ratio was a significant parameter that had an effect on the dynamic strength. The main pulse load was concentrated in a zone whose size was no larger than the shell diameter.

Authors [4] studied the behavior of carbon- and glass fiber based fabrics under high-speed tension within the strain rate range of about $\sim 10^3\text{–}10^4\ \mathrm{s}^{-1}$. The load-carrying capacity of materials under high-speed tension was assessed by the well-known method — blasting of an explosive charge inside a hollow cylindrical shell [2]. Studied were TS-8/3-250 glass fabric and UUT-2 carbon fabric. In order to avoid any undesirable edge effects in loading, the experiments were performed on cylindrical shells of length equal to two times diameter and involved blasting of a ball-shaped trotyl-hexogen explosive charge within the shell. The shells with internal radius R, length $4R$, and thickness δ were prepared by winding the fabric in such a way that its base was oriented circumferentially. The experiments were set up similar to those in [2]. Each shell was subjected to a single loading. The findings confirmed the conclusion [2] that the reinforcing base of GRE is its main load-bearing element under critical pulse loading conditions.

Fedorenko et al. [5] studied the scale effects on the load-carrying capacity and deformation parameters of fiberglass reinforced plastic (FRP) shells under a single internal pulse loading. The experiments were carried out in a wider scale range (9.3-fold) than that (4.4-fold) in [1]. The investigation was focused on strains and failure of open-ended geometrically similar FRP shells. The experimental setting and methods of recording were detailed in [2]. The shell failure and fracture pattern (number of cracks and their precursors) were identified as in [1, 2]. The shells made of FRP based on a fabric similar to that in [2] were used in the experiments. The shell length was four times inner radius R, the thickness ratio δ/R was 6%. The shells were of two characteristic sizes: with inner radius 75 mm (type I) and 700 mm (type II). No scale effect of energy nature, whereby strength would decrease manyfold, was observed in the experiments on cylindrical FRP shells loaded with an internal explosion in air. As in [3], it was demonstrated that the shell failure was caused by the loss of stability of the shell axisymmetric vibrations and transformation of vibration energy into a bending mode, resulting in attainment of the critical strain value in the shell local volumes.

Ivanov and Tsypkin [6] discussed and generalized the main experimental findings [1–5], specified the factors and parameters governing the load-carrying capacity of shells under extreme pulse loads. Dynamic fracture behavior of steel and FRP shells and the physical nature of the scale effect were considered from a unified standpoint. FRP shells were demonstrated to have significant advantages over steel ones under extreme pulse loads.

The objective of work [7] was to assess coefficients of variation of the ultimate load and ultimate strain for cylindrical FRP shells under internal pulse loading. The experiment setting-up and methods of recording were similar to those described in [2]. The tests were performed on cylindrical FRP shells into which steel shells (steel 20) had been inserted gapless. The FRP shells were made by "wet" winding of ÉDT-10-binder-impregnated RVNM10-1260-80 roving, with alternating circular and spiral ($\varphi = \pm 35°$) plies. Hereinafter, φ is the reinforcement (winding) angle with respect to the generatrix. The investigations demonstrated that FRP shells under extreme pulse loading conditions have a higher strength (in comparison to the static loading case) by the ultimate strain criterion and a sufficient stability thereof.

Tsypkin et al. [8] looked at how the reserves of strength of FRP in a shell type structure under internal pulse loading can be used to the best advantage. The studied deformation and fracture of cylindrical two-layer metal-plastic shells (a steel 20 shell inserted gapless into a FRP shell) under internal explosion loading. The experiment setting-up and methods of recording were as detailed in [2]. The shells that survived the first loading were then subjected to further loading. The shell fracture and its precursors (the FRP shall locations becoming lighter in color) were identified as in [1]. Two types of TS-8/3-T fabric based FRP (similar to that described in [2]) shells were used: inner radius = 100 mm, thickness = 16 mm (type I), and inner radius = 100 mm, thickness = 7 mm (type II). The mass of the equi-thickness steel layer in the metal-plastic shells was varied as follows: 1.7, 3.42, and 8.14 kg. The investigations demonstrated, in view of the data [2, 3], essential advantages of using metal-plastic shells in thin-walled structures to operate under extreme pulse loading conditions.

The study [9] was aimed at clarifying the influence of a significant increase in elasticity of a binder of the composite shell on the shell dynamic response and strength under pulse loading at strain rates up to $10^3\ \text{s}^{-1}$. The shells were made of glass fiber (VMPS yarn) and SVM organic fiber. The experiment setting-up and methods of recording were as detailed in [2]. The shells that survived the first loading were then subjected to further loading (up to three times). Four types of FRP shells (types I and II) and organic fiber plastic (OFP) shells (types III and IV) were used; they had the same inner radius $R = 150$ mm, length $4R$, and thickness ratio $\delta/R = 8.5–11.9\%$, a similar reinforcement arrangement but differed in the binder elasticity. The shells were prepared by a combined winding of yarn tapes, with alternation of spiral ($\varphi = \pm 45\ldots 60°$) and circular ($\varphi = \pm 90°$) plies, their thickness ratio being 1:1. For types I and III shells the ÉDT-10 epoxy binder was used, while the shells of types II and IV involved a high-elasticity epoxy binder with unit elongation of about 30%. It was found out that: (i) all the shells studied deform elastically till fracture, which is in agreement with the findings [1–5]; (ii) the change in the binder elasticity has an effect on the damping properties: damping of vibrations in the shells with a high-elasticity binder occurs somewhat sooner in comparison to ÉDT-10 epoxy binder; (iii) strength and dimensional instability of cylindrical shells, which were made by wet winding of fiberglass yarn and organic fiber yarn, under internal explosion loading and at strain rates up to $700\ \text{s}^{-1}$ are governed by the fiber type and properties and are almost independent of the binder elasticity.

Fedorenko et al. [10] experimentally studied the influences of the glass fabric structure and material on the dynamic response and strength of shells with various thickness ratios. The tests were carried out on circular cylindrical shells made by winding a plain-woven T-25 grade glass fabric impregnated with an epoxy binder. The shells had an inner radius $R = 100$ mm, length $2R$, and thickness ratios $\delta/R = 2.5$, 5, 10, 15, and 20%. Dynamic loading of the shells was performed through blasting a centrally located cylindrical explosive charge. The experiment setting-up and methods of recording were as detailed in [1, 3]. The shells that survived the first test were then subjected to further loading (up to three times). The experiments with internal explosion loading in air at strain rates up to ~ 600 s^{-1} revealed an essential effect of initial properties, material structure, and thickness ratio of the circular cylindrical GRE shells on the dynamic response, fracture mechanism, and load-carrying capacity.

Syrunin et al. [11] undertook an experimental comparison of various reinforcement (winding) configurations for cylindrical GRE shells on the dynamic response and strength of the shells under internal explosion loading. Tested were the shells prepared by winding the tapes of VMPS type glass fiber yarns impregnated with ÉDT-10 epoxy binder. The yarns were wound on a process mandrel, at a preset angle φ to the shell generatrix. Four types of cylinders were tested: inner radius $R = 155 \pm 5$ mm, length $4R$, and wall thickness ratios $\delta/R = 9.3$–10.9%. The reinforcement configurations were as follows: (1) alternating spiral plies with an angle $\varphi = \pm 30°$; (2) alternating spiral ($\varphi = \pm 60°$) and circular ($\varphi = \pm 90°$) plies, their thickness ratio being 1:1; (3) alternating spiral ($\varphi = \pm 60°$) and circular ($\varphi = \pm 90°$) plies with a thickness ratio 1:2.5; and (4) circular winding of the plies ($\varphi = \pm 90°$). The investigations demonstrated that the reinforcement configuration of GRE has a significant effect on the stress-strain state, load-carrying ability, and fracture behavior of the shells under explosion loading. The highest specific load-carrying ability is exhibited by the material with alternating double spiral and circular plies of equal thickness.

The publication [12] addressed an experimental study of the influence of configuration of multiple-ply winding of high-modulus fiber yarn or roving tapes on the stress-strain state and specific load-carrying ability of circular cylindrical shells under explosion loading in air by using a ball-shaped explosive charge located at the center of the shell. The cylindrical test specimens had an inner diameter $2R = 300$–320 mm, length 600 mm, and wall thickness ratios $\delta/R = 8 \pm 2.9$%. The following reinforcement configurations were considered: (1) alternating spiral plies with a reinforcement angle with respect to the generatrix $\varphi = \pm 30°$; (2) alternating spiral ($\varphi = \pm 60°$) and circular ($\varphi = \pm 90°$) plies, their thickness ratio being 1:1; (3) alternating spiral ($\varphi = \pm 60°$) and circular plies with a thickness ratio 1:2.5; (4), (11) circular winding; (5)–(8) spiral reinforcement ($\varphi = \pm 30$, ±45, ±50, and ±60°, respectively); (9), (10) spiral-circular winding of plies ($\varphi = \pm 90$, ±45, and ±60°) with a thickness ratio 1:1. The test results for specimens of type (1)–(4) were given in [11]. These specimens were prepared using VMPS yarn reinforcement scheme, while specimens of types (5)–(11) were based on RVMN roving. The ÉDT-10 binder was used in all the reinforcement configurations. Specimens were loaded one, two or three times until fracture.

As in publications [1–7, 9–11], the time variations of radial expansion in the shell central section were noted by the high-speed photo-recording method; circumferential and meridian strains were measured by strain gauges in the same section and, for some specimens, in sections at a distance of 50, 100, and 200 mm from the central one along the generatrix. The experimental findings enable one to infer that the combined reinforcement configurations with alternating circular and spiral plies almost equal in thickness are preferable in order to ensure the highest values of specific load-carrying ability of circular GRE shells under internal explosion loading in air.

Fedorenko et al. [13] experimentally determined the ultimate circumferential strain in wound-type GRE under the conditions of centrally symmetric explosion loading, where various levels of deformation biaxiality were implemented by filling the shells with air or water. The test specimens were cylindrical GRE shells prepared by wet winding of VM-1 fiber roving tapes pre-impregnated with an epoxy binder. The shells had an inner radius $R =$ 77.5 mm, length $4R$, and thickness ratios $\delta/R = 4.6$–7.7%. A combined reinforcement configuration was used, which involved alternation of double spiral ($\varphi = \pm 45°$) and circular ($\varphi = \pm 90°$) plies with their thickness ratio 2:1. In some tests, steel 20 shells with an inner radius $R_1 = 76.5$ mm and thickness ratio $\delta_1/R_1 = 1.3$% (δ_1 is the steel shell thickness) were into the GRE shells with a minimum gap (max. 0.25 mm). The shell was subjected to a single explosion loading. The experimental set-up and methods of recording were as detailed in [1–6, 9–11].

The investigations have shown that in the case of wound-type GRE with a spiral-circular reinforcement configuration the ultimate strain depends on the breaking strain of elementary fibers that experience the largest tension in circular plies. As in the case of fabric-based GRE [2–6, 10], this parameter can be used as a strength criterion if the load-carrying ability of the material is exhausted during a high-speed loading.

The publication [14] presented an experimental study of the effect of reinforcement configurations on the ultimate strains in GRE cylindrical shells subjected to radially symmetric loading and on the their fracture conditions during the first phase of tension. The test specimens were cylindrical GRE shells prepared by winding, on a technological mandrel, the VM-1 fiber roving tapes pre-impregnated with an epoxy binder. There were three types of shells which had an inner radius $R = 150$ mm, length $4R$, and wall thickness ratios $\delta/R = 4.8$–7%. Three reinforcement configurations were used: (1) circular winding of plies; (2) alternating spiral ($\varphi = \pm 45°$) and circular ($\varphi = 90°$) plies with their thickness ratio 1:1; and (3) alternating spiral ($\varphi = \pm 65°$) and circular ($\varphi = 90°$) plies with their thickness ratio 1:1. In the cases (1) and (2), steel 20 shells with an inner radius $R_1 = 147.5$ mm and wall thickness ratio $\delta_1/R_1 = 1.35\%$ were inserted into the GRE shells with a minimum gap (max. 0.5 mm) in order to suppress the bending fracture mechanism in vibrations and to make the best use of the load-carrying ability [7, 8]. The test shells were subjected to a single internal explosion loading by blasting a ball-shaped explosive charge located at the shell center. The experimental set-up and methods of recording were as detailed in [6–9, 11].

The experiments demonstrated that for the wound-type-oriented GRE material with a combined spiral-circular reinforcement configuration the ultimate circumferential strain in dynamic tension was independent of the spiral plies winding angle within the range studied ($\varphi = 35$–65°). Its magnitude was $4.8 \pm 0.4\%$ and depended on the breaking strain in elementary fibers that experienced the greatest tension in circular plies under these loading conditions. As in the case of fabric-type GRE materials [6], the ultimate strain can serve as a strength criterion under dynamic loading. This conclusion applies to the composites whose structure permits realizing the ultimate tensile strength of load-bearing fibers. If the structure and loading mode allow for the presence of ultimate shear stresses or the binder rupture before the tensile stresses in fibers reach their breaking value, then the strength and deformation characteristics of the load-bearing base are not fully utilized. For instance, in [11] this effect was observed for the shells prepared by spiral winding with $\varphi = \pm 30°$ (without winding of spiral plies). Thus, the glass fiber which is a load-bearing element of the GRE material [6] dictates the material's ultimate dynamic deformation characteristics irrespective of the reinforcement angle of less-loaded plies provided that there are plies whose fibers' orientation coincides with the leading component of tensile stresses.

The experimental investigations [1–5, 7–14] were briefly reviewed in [15] noting the main features of behavior of the composite shell under internal explosion loading conditions, and the advantages of these materials over steel.

Syrunin et al. [16] studied the dynamic response and load-carrying ability of shells subjected to an internal explosion loading. The shells were made of oriented GRE using VM-1, VMP, R, and Kh fiber roving tapes, the reinforcement configurations being the same for all the shells. In addition, similar tests were carried out on the shells made of SVM organic fiber-reinforced plastic.

For the purpose of comparative analysis of the fibers' resistance to a pulse load, the criterion proposed in [9] was used. The test pieces were cylindrical shells prepared by combined winding of tapes impregnated with an epoxy binder, with alternating double spiral ($\varphi = \pm 45°$) and circular ($\varphi = \pm 90°$) plies with their thickness ratio 1:1. The shells had an inner radius $R = 150$ mm, length $4R$, and wall thickness ratio $\delta/R = 4.18$–6.0% ($\delta/R = 2.45$–2.7% for Kh grade glass fiber-reinforced plastic shells and $\delta/R = 8.2$–8.6% for organic fiber-reinforced ones). The GRE shells were reinforced with roving tapes, while the organic-based ones were reinforced with fiber bundles: (1) VM-1 glass fiber, RVMN 10-1260-80 roving; (2) VMP glass fiber, RVMPN 10-1200-78 roving; (3) R glass fiber, RRN 10-1400-78 roving; (4) Kh glass fiber, RKhN 9-925-78 roving; (5) SVM organic fiber, ZhSVM 3-300-58.8x17-1000 bundle. The epoxy binder ÉDT-10 was used in all the shell types. The dynamic loading was implemented through blasting a ball-shaped charge of trotyl-hexogen mixture. Two series of experiments were carried out: (a) on cylindrical GRE shells of all types, and (b) on cylindrical GRE shells into which steel 20 shells with an inner diameter $2R_1 = 295$ mm, length $4R$, and wall thickness ratio $\delta_1/R_1 = 1.35\%$ were inserted with a gap of max. 0.2 mm, the shells' thickness ratio being $\delta_1/\delta = 0.2$–0.3. The tests showed that the ultimate deformability of the load-bearing element of the composites – the fiber – under dynamic tension conditions is the governing criterion, in combination with elastic and mass characteristics of the composite, for the specific strength of shell type structures under pulse loading.

The publication [17] provided a more detailed (in comparison to [2, 6, 12]) study of the effect of the number of loadings of various levels on the ultimate breaking strain of cylindrical shells of wound-type glass reinforced plastic in a wide range of explosion loads. The test pieces were circular cylindrical shells made by wet winding of RVMGN10-1260-80 roving (based on VM-1 glass fiber) tapes impregnated with ÉDT-10 epoxy binder. The shells had a combined reinforcement configuration, where double spiral plies ($\varphi = \pm 45°$) were alternated with circular plies ($\varphi = \pm 90°$), their thickness ratio being 1:1. The shells were of inner radius $R = 150$ mm, length $4R$, and wall thickness ratio $\delta / R = 4.8$–6.7%. Similar shells were studied in [12, 14].

The experiments demonstrated that for cylindrical shells made of oriented GRE there is a critical level of strains whereby the structure would withstand a given number of internal explosion actions. The magnitude of this critical strain linearly depends on the log number of loadings to fracture. Also, for this type of GRE there is a limit level of explosion action whereby the number of non-breaking loadings can be fairly large ($> \approx 10^2$). This level is achieved at loads which are about one order of magnitude lower than the ultimate ones in a single explosion action.

Ryzhanskii et al. [18] addressed the internal explosion loading of cylindrical shells (a single-layer GRE one and a two-layered – metal-plastic – shell) by blasting a ball-shaped charge of trotyl-hexogen mixture located at the shell center. The metal layers were made of steel 20 and PT-3V titanium alloy. The reported experimental results (maximum latitudinal strains in the shell) were obtained in deformation without fracture or at an early stage of fracture, where minor ruptures of glass yarns on the external surface of the layer took place. For GRE shells the wall thickness ratio was varied in the range $\delta / R = 2.5$–20%, for the metal-plastic shells $\delta / R = 5.3$–16%, $\delta_1 / \delta =$ 0.062–0.47. Based on the analysis of the experimental findings, a method for a priori assessment of the shell explosion resistance was elaborated. Semi-empirical formulas were put forward, which were recommended to be used in the design of explosion-protection chambers with load-carrying shells made of the above-mentioned materials.

In [19], an integral approach to the fracture problem was stated; it implied a manifestation of strong scale effects of energy nature (SEEN). The results of many years' experimental investigations of behavior of cylindrical shells (including GRE ones) under explosion loading [1–5, 7–14, 16–18, et.] were analyzed. It was noted that fiber-reinforced composites underwent fracture with no SEEN manifestation. The publication demonstrated the advantages of these materials over steels, showed their deformation and fracture behavior depending on the reinforcement configuration, geometrical dimensions, material composition, strain rate, proposed several types of design for explosion-resistant containers, and defined a concept of the development of high-reliability localizing chambers for power engineering of explosion-type thermonuclear fusion.

Rusak et al., [20] experimentally studied the main characteristics of dynamic deformation behavior and strength of tubular shells made of basalt fiber-reinforced plastic under internal explosion loading conditions. The tests were performed on shells with unidirectional reinforcement, based on ÉDT-10 binder and roving of basalt fiber yarns RB9-1200 with 4S spin finish. The shells had the following geometrical dimensions and reinforcement parameters: (1) inner diameter $D = 150$ mm, length $L = 300$ mm, thickness $\delta = 6.6 \pm 0.2$ mm, reinforcement angles $\varphi \approx \pm 90$ and $\pm 35°$ with respect to the generatrix, alternation of seven double circular plies and seven double spiral plies, the mean mass concentration of the binder (16.3 ± 0.6)%; (2) $D = 295$ mm, $L = 600$ mm, $\delta = 13.5 \pm 0.5$ mm, $\varphi \approx \pm 90$ and $\pm 35°$ with respect to the generatrix, alteration of 14.5 double circular plies and 10 double spin plies, the mean mass concentration of the binder (21.3 ± 0.6)%. Generally, the reinforcement configuration corresponded to that ensuring a high specific strength of cylindrical shells made of high-modulus fiber-reinforced composites [12] under similar explosion loading conditions.

The shells were prepared by wet winding onto a technological mandrel, followed by heat treatment. Prior to testing, steel shells of thickness $\delta_1 = 1$ and 2 mm were inserted into most shells of type 1 and 2, respectively. This outer diameter of the steel shells ensured the minimum gap to the inner surface of the basalt-plastic shell. For monitoring the circumferential strain in the shell's section where the explosive charge was located, the nichrome-wire strain gauges were used with bifilar winding along the entire circumference [21].

The radial expansion of the shell in its central section was measured by high-speed slit-type photo-recording [22]. Every specimen was subjected to a single explosion loading (it was only in one case that the undamaged shell was reloaded). Based on the experiments, the following conclusions were made: (i) the dynamic response of basalt-plastic shells under nonbreaking loads is similar to that of GRE shells which have a close reinforcement configuration and whose material's elastic properties determined under static loading remain unchanged under dynamic loading conditions; (ii) the ultimate dynamic deformability and specific strength of basalt-plastic tubes under internal explosion loading remain unchanged as the specimen size is doubled and their magnitudes are lower in comparison to GRE shells.

The publication [23] generalized the experimental findings regarding dynamic response and strength of cylindrical and spherical shells of fiber-reinforced composites [1–5, 7–14, 16–18, 20, etc.] and thus substantiated the choice of these materials for load-bearing elements of explosion-protection structures, noted the advantages of using composites over structural steels for such applications, put forward and experimentally substantiated the criterion for selecting an appropriate type of fibers, established the reinforcement configurations to provide composites with an optimal strength/mass ratio for the shells of load-bearing enclosures of explosion-protection containers and chambers.

According to [24], a shell is considered thick-walled if its thickness-to-inner radius ratio is larger than 1/10. In almost all the experiments [1–5, 7–14, 16–18, 20] both thin- and thick-walled shells were studied.

In addition to the above-mentioned publications, noteworthy are also the works which experimentally studied the stiffness and strength characteristics, the influence of strain rate on mechanical properties of composite materials, and other factors [25–27, etc.].

Alekseev et al. [25] performed an experimental investigation of static stiffness and strength characteristics of organic- and glass-fiber-reinforced plastics. The deformation behavior of tubular specimens of these composite materials was shown to essentially depend on the loading mode and winding angle. The dependences of elastic moduli and ultimate stresses on the reinforcement angle were clarified.

The publication [26] reported the results of an experimental study of strength of anisotropic GRE materials of various grades at strain rates 10^{-4}–62.5 s^{-1}. It was found out that in comparison to static strength the dynamic strength characteristics of the material increased with stress growth rate in tension, compression, and simple shear. It was shown that the safe stress state regions bounded by limit ellipses grew with increasing strain rate; as this took place, the limit ellipses underwent extension as well as deformation.

Aseev et al. [27] experimentally studied the effect of strain rate on the mechanical characteristics of unidirectional epoxy-based composites: tubular specimens of glass- and organic fiber-reinforced plastics with a winding angle $\varphi = \pm 90°$. The tests were carried out by several procedures covering the strain rate range $\dot{\varepsilon} \cong 10^{-1}$ – $2.5 \cdot 10^3\ s^{-1}$. The test materials were GRE composites based on VM glass fibers and ÉDT-10 binder and organic-plastic composites based on SVM organic fibers and ÉDT-10 binder. In the strain rate range $\dot{\varepsilon} \cong 30$–$250\ s^{-1}$ these materials were found to deform elastically till fracture. The ultimate strain grows with increasing strain rate: from 2% (at $\dot{\varepsilon} = 50\ s^{-1}$) to 4% (at $\dot{\varepsilon} \cong 250\ s^{-1}$) for GRE and from 1.3% (at $\dot{\varepsilon} = 30\ s^{-1}$) to 2.3% (at $\dot{\varepsilon} \cong 150\ s^{-1}$) for organic-fiber-reinforced composite.

A comparison between the results of static and dynamic testing of composite materials of these two types suggests that (a) they feature linear deformation curves over the entire strain rate range; (b) within the accuracy of determination of static and dynamic elastic modulus this quantity is independent of the strain rate; (c) for the both types of wound composites the ultimate strain increases 1.7–2.3 times within the strain rate range studied.

The publication [28] addressed an experimental determination of special features of the response to loading and of the ultimate strength characteristics of main load-bearing elements and structure of cylinder-shaped explosion-protection container (EPC), where the load-bearing enclosure is made of oriented GRE, during the blasting of an explosive charge inside the container [28]. The data obtained were used for the design of a metal-composite EPC of diameter 2.5 m, length 9.5 m, mass 25 t capable to withstand an explosion of up to 150–200 kg TNT.

A wide use of explosion-protection containers in various industries was noted in [29, 30]. The publication [29] provided a historical review of R&D efforts aimed at designing such structures in the USA, former USSR, UK, China, and other countries. It follows from [29] that all the above-mentioned experimental investigations [1–3, 6–8, 11, 13–15, 17, 20, 23] of composite shells were carried out in Russia, and the design procedures for composite EPCs were put forward there as well. The work [29] gives the classification of EPCs and the most widely used EPC designing methods, including those that involve cylindrical and spherical shells of composite materials. The authors [29] believe that composites are promising materials for EPCs and that further theoretical and experimental studies of strength of structures made of such composites would be of great importance. The publication [30] reviewed the theoretical and experimental investigations of the phenomenon of excitation of vibrations in cylindrical and spherical vessels under the internal explosion loading conditions.

The review [31] noted only one publication addressing the experimental study of dynamics (of natural vibrations) of a composite cylindrical shell.

Some results of experimental determination of characteristics of natural, forced, and parametric vibrations of multilayer composite shells of revolution, including cylindrical ones, can be found in [32].

The analysis of the publications reviewed here above has demonstrated the following.

1. Almost all the available experimental investigations of composite and metal-composite shells under internal explosion were carried out in Russia (Russian Federal Nuclear Center – All-Russian Research Institute of Experimental Physics).

2. In the experiments on hollow composite cylinders (both thin- and thick-walled ones) loaded by blasting an explosive charge the wound-type glass- and basalt-fiber-reinforced composites have been found to have significant advantages over steels and titanium alloys in some main properties important for explosion resistance, namely:

(i) no scale effects of strength degradation during a geometrically similar increase of dimensions with the diameters and material of the load-bearing fibers remaining unchanged;

(ii) a larger specific strength in comparison to the above-mentioned metals;

(iii) insusceptibility to minor defects;

(iv) non-catastrophic and non-shattering fracture mode;

(v) a strength-optimal anisotropy can be selected;

(vi) strength properties and ultimate strains grow with increasing strain rate.

3. Irrespective of the strain rate, the composites deform elastically till fracture that occurs at strains corresponding to the metals' plastic state. Circumferential elastic modulus of GRE is independent of the strain rate over the strain range studied.

4. Strength and deformability of cylindrical shells made of glass- and organic-fiber-reinforced composites are almost independent of the binder elasticity.

5. The shell fracture pattern under internal explosion loading depends on the shell thickness. Fracture starts from the external surface in thin-walled shells and from the internal surface in thick-walled ones.

6. The experimentally studied composites have a low thermal stability of their matrix, a low cyclic strength and dynamic stability of radial vibrations of pulse-loaded shells. This impairs the reliability of structures and narrows the potentiality of independent use of such composites for explosion protection purposes.

7. The enhancement of the load-bearing composite shell by inserting a thin steel shell into it eliminates the above-mentioned drawbacks, except for the low cyclic strength. Therefore, the shells of this type are best used in single-loading cases. A further increase in the shell's specific loading-carrying ability and ultimate strain is achieved by adding an enhancing damping layer of steel with a thickness $\geq 1/8$ of GRE thickness, which prevents the parametric loss of stability and failure of the elastic composite shell under smaller loads. The combined shell is more energy intensive with a smaller mass in comparison to a metal shell, and its metal layer protects the composite against fragments in explosion.

8. The experiments have demonstrated a significant influence of the reinforcement configuration and thickness ratio of circular cylindrical GRE shells on the shells' dynamic response, fracture pattern and mechanism, and on the load-carrying ability under internal explosion loading in air. The highest specific load-carrying ability of shells under a centrally symmetric explosion loading is achieved in the case of cylindrical composite shells based on GRE with alternation of spiral layers (the reinforcement angle φ being 30–65°) and circular layers of equal thickness.

9. In the case of dynamic loading of wound-type GRE with a spiral-circular reinforcement configuration the ultimate strain depends on the breaking strain of elementary fibers that experience the largest tension in circular plies. This strain can serve as a strength criterion when the load-carrying capacity of the material is exhausted during high-speed loading. The limit strain value for circular plies (4.8–5.0%) in a shell under explosion loading has been found to be insensitive to variation of reinforcement angle of neighboring spiral plies and to the extent of their loading.

10. The issue of optimal design of composite cylindrical shells to operate under internal explosion loading has not been thoroughly studied experimentally.

11. Due to a high cost of experimental investigations, a large number of plies, a great diversity of their mechanical characteristics, reinforcing elements, reinforcement configurations, etc., the experimental investigations have been noted to be of limited potentiality, in comparison to theoretical ones for the large-scale study of deformation, fracture, and optimal design of composite shells.

12. The investigations reviewed herein have made it possible to design several EPCs both in Russia and abroad.

REFERENCES

1. V. M. Ryzhanskii, V. N. Mineev, A. G. Ivanov, et al., “Failure of water-filled cylindrical glass-epoxy shells under internal pulse loading,” *Mekh. Polimer.*, No. 2, 283–289 (1987).
2. V. I. Tsypkin, V. N. Rusak, A. T. Shitov, and A. G. Ivanov, “Deformation and failure of cylindrical glass-epoxy shells under internal pulse loading,” *Mekh. Kompoz. Mater.*, No. 2, 249–255 (1981).
3. A. G. Fedorenko, V. I. Tsypkin, A. G. Ivanov, et al., “Special features of dynamic deformation and failure of cylindrical fiberglass reinforced plastic shells under internal pulse loading,” *Mekh. Kompoz. Mater.*, No. 1, 90–94 (1983).
4. V. I. Tsypkin, V. N. Rusak, and A. G. Ivanov, “High-speed tension of inorganic-fiber fabrics,” *Mekh. Kompoz. Mater.*, No. 1, 161–163 (1986).
5. A. G. Fedorenko, V. I. Tsypkin, A. G. Ivanov, et al., “Deformation and failure of nonuniformly scaled cylindrical fiberglass reinforced plastic shells under internal pulse loading,” *Mekh. Kompoz. Mater.*, No. 4, 658–664 (1986).
6. A. G. Ivanov and V. I. Tsypkin, “Deformation and failure of fiberglass reinforced plastic shells under extreme pulse loads,” *Mekh. Kompoz. Mater.*, No. 3, 472–480 (1987).
7. O. S. Vorontsova, M. A. Syrunin, A. G. Fedorenko, et al., “Experimental study of coefficients of variation of strength characteristics of fiberglass reinforced plastic shells under internal pulse loading,” *Mekh. Kompoz. Mater.*, No. 4, 642–646 (1987).
8. V. I. Tsypkin, V. N. Rusak, A. G. Ivanov, et al., “Deformation and failure of two-layer metal-plastic shells under internal pulse loading,” *Mekh. Kompoz. Mater.*, No. 5, 833–838 (1987).
9. A. G. Fedorenko, V. I. Tsypkin, M. A. Syrunin, et al., “Behavior of composite shells with a high-elasticity binder under internal pulse loading,” *Mekh. Kompoz. Mater.*, No. 2, 306–314 (1988).
10. A. G. Fedorenko, A. G. Ivanov, M. A. Syrunin, “Dynamic strength of fiberglass reinforced plastic shells,” *Mekh. Kompoz. Mater.*, No. 3, 425–430 (1989).
11. M. A. Syrunin, A. G. Fedorenko, A. T. Shitov, “Strength of cylindrical shells made of variously structured fiberglass reinforced plastic under explosion loading,” *Fiz. Goren. Vzryva*, No. 4, 108–115 (1989).
12. A. G. Fedorenko, M. A. Syrunin, and A. G. Ivanov, “The influence of reinforcement structure of oriented fiberglass plastics on the strength of circular cylindrical shells,” *Mekh. Kompoz. Mater.*, No. 4, 631–640 (1991).
13. A. G. Fedorenko, M. A. Syrunin, A. G. Ivanov, “Ultimate strains in shells made of oriented fiber composites under internal explosion loading,” *Fiz. Goren. Vzryva*, No. 2, 87–93 (1992).
14. A. G. Ivanov, A. G. Fedorenko, and M. A. Syrunin, “The effect of reinforcement structure on the ultimate deformability and strength of oriented fiberglass reinforced plastic shells under internal explosion loading,” *Prikl. Mekh. Teor. Fiz.*, No. 4, 130–135 (1992).

15. A. G. Fedorenko, M. A. Syrunin, A. G. Ivanov, "Dynamic strength of shells of oriented fiber composites under internal explosion loading (review)," *Prikl. Mekh. Teor. Fiz.*, No. 1, 126–132 (1993).
16. M. A. Syrunin, A. G. Fedorenko, and A. G. Ivanov, "Dynamic strength of shells of oriented composites based on fibers of various compositions," *Prikl. Mekh. Teor. Fiz.*, No. 3, 141–145 (1995).
17. M. A. Syrunin, A. G. Fedorenko, and A. G. Ivanov, "Dynamic strength of cylindrical fiber glass composite shells under multiple explosion loading," *Fiz. Goren. Vzryva*, No. 6, 102–107 (1997).
18. V. A. Ryzhanskii, V. N. Rusak, and A. G. Ivanov, "Assessment of explosion resistance of cylindrical composite shells," *Fiz. Goren. Vzryva*, No. 1, 115–121 (1999).
19. A. G. Ivanov (Ed.), *Fracture of Non-Uniformly Scaled Objects under Explosion. Monograph* [in Russian], RFYaTs-VNIIÉF, Sarov (2001).
20. V. N. Rusak, A. G. Fedorenko, M. A. Syrunin, et al., "Ultimate deformability and strength of basalt-plastic shells under internal explosion loading," *Prikl. Mekh. Tekhn. Fiz.*, No. 1, 186–195 (2002).
21. A. T. Shitov, V. N. Mineev, O. A. Kleshchevnikov, et al., "Tensometer for continuous recording of large strains in a structure under dynamic loading," *Fiz. Goren. Vzryva*, No. 2, 304–307 (1976).
22. A. S. Dubovik, *Photographic Recording of Fast Processes* [in Russian], Nauka, Moscow (1975).
23. A. G. Fedorenko, M. A. Syrunin, and A. G. Ivanov, "Criteria for choosing materials for shell structures to localize explosions (review)," *Fiz. Goren. Vzryva*, No. 5, 3–13 (2005).
24. A. Onder, O. Sayman, T. Dogan, and N. Tarakcioglu, "Burst failure load of composite pressure vessels," *Compos. Struct.*, **89**, 159–166 (2009).
25. K. P. Alekseev, R. A. Kayumov, I. G. Teregulov, and I. Kh. Fakhrutdinov, "Mechanical characteristics of organic- and carbon-fiber-reinforced plastic pipes made by cross-ply winding," *Mekh. Kompoz. Mater. Konstr.*, No. 4, 51–61 (1998).
26. V. A. Kopnov and V. A. Koloti1ov, "Strength of anisotropic glass-reinforced plastics with a complex stressed state and high loading rate," *Strength Mater.*, **21**, No. 3, 279–284 (1989).
27. A. V. Aseev, N. N. Gorshkov, A. G. Demeshkin, et al., "Experimental investigation of deformability of glass- and organic-fiber-reinforced composites as a function of strain rate," *Mekh. Kompoz. Mater.*, No. 2, 183–195 (1992).
28. M. A. Syrunin, A. G. Fedorenko, and A. G. Ivanov, "Loading response and strength of fiberglass plastic container under internal explosion loading," *Fiz. Goren. Vzryva*, No. 3, 127–136 (2002).
29. J. Zheng, Y. Chen, G. Deng, et al., "Recent progress of explosion containment vessels. Pt. I: Methods for design of explosion containment vessels," *J. Press. Equip. Syst.*, No. 6, 185–198 (2008).
30. J. Zheng, Q. Dong, and Q. Li, "Recent progress of explosion containment vessels. Pt. II: Strain growth in explosion containment vessels," *J. Press. Equip. Syst.*, No. 6, 199–207 (2008).
31. M. S. Qatu, R. W. Sullivan, and W. Wang, "Recent research advances on the dynamic analysis of composite shells: 2000–2009," *Compos. Struct.*, No. 93, 14–31 (2010).
32. *Mechanics of Composites* [in Russian], in 12 volumes, Vol. 9: *Dynamics of Structural Members*, Naukova Dumka, Kiev (1999).