

Supplemental information

Advanced functional safeguarding composites with enhanced anti-impact and excellent thermal properties

Table S1. The fitting parameters of KFRP in vertical type

KFRP	E_0 (MPa)	β	σ_e	n_e	A	n
5%	6.28	0.51	0.11	0.76	1.34E15	23.77
10%	5.68	1.08	0.22	0.65	207.87	29.41
15%	55.80	0.68	0.95	2.11	-0.77	9.05

Table S2. The material parameters of KFRP

	SSE	KFRP-5%	KFRP-10%	KFRP-15%
Tensile strength in vertical (MPa)	0.12	0.50	0.86	2.62
Tensile strength in horizontal (MPa)	0.13	0.37	0.71	0.99
Tensile toughness in vertical (kJ/m ²)	12.33	66.00	86.17	135.83
Tensile toughness in horizontal (kJ/m ²)	13.67	54.17	97.67	93.00
Fracture toughness in vertical (kJ/m ²)	0.51	6.71	10.56	11.95
Fracture toughness in horizontal (kJ/m ²)	0.67	3.37	6.02	9.56
Thermal conductivity (W/mK)	0.18	0.20	0.22	0.25
Thermal diffusivity (mm ² /s)	0.13	0.14	0.18	0.20
Specific heat (MJ/m ³ K)	1.47	1.41	1.25	1.22

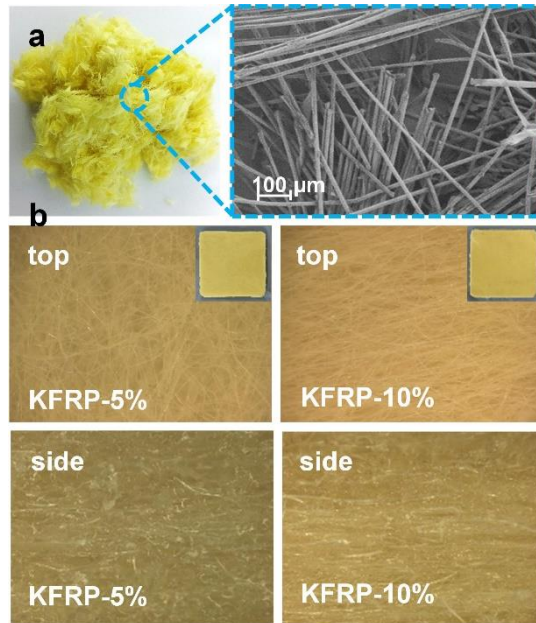


Fig. S1. (a) Photograph of KFs and their SEM image. (b) The surface and cross-sectional morphology of KFRP-5% and KFRP-10%.

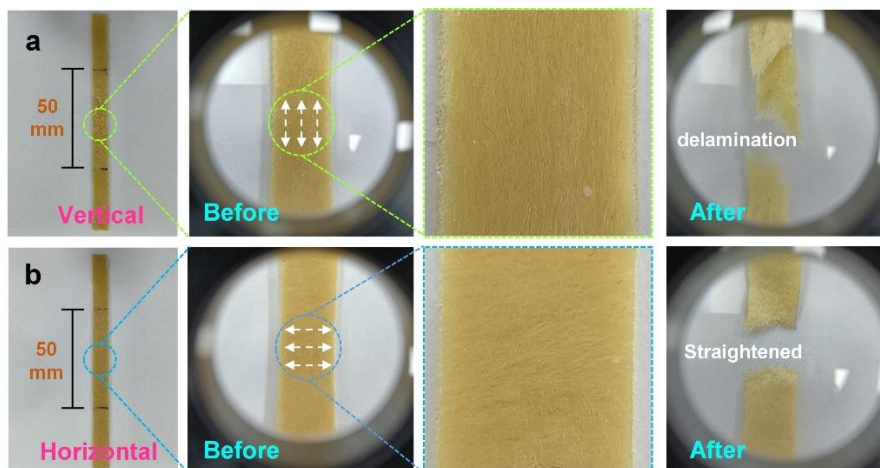


Fig. S2. Two stretching definitions of KFRP have different fiber directions: (a) vertical and (b) horizontal and the photos before and after the tensile test.

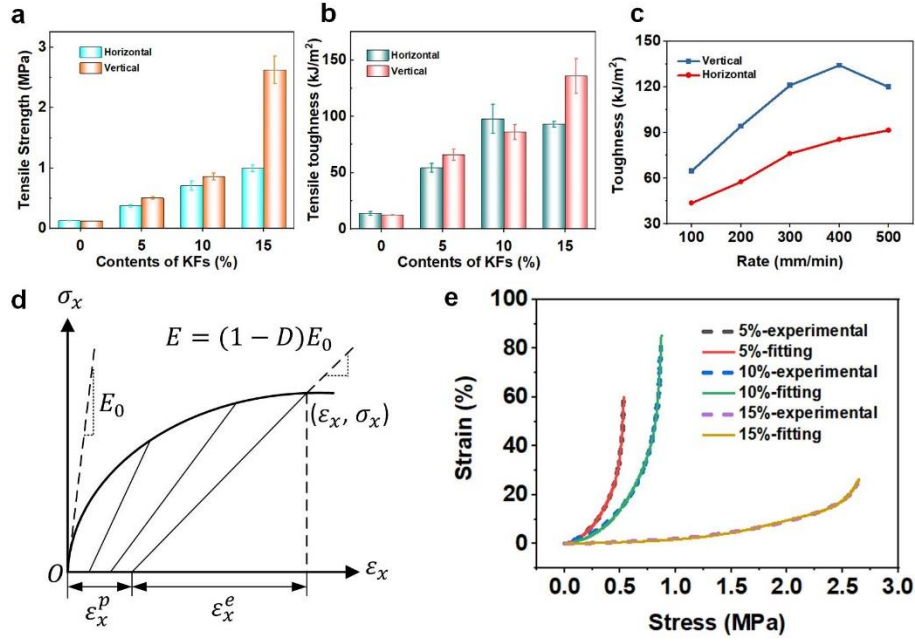


Fig. S3. (a) Tensile strength and (b) tensile toughness of KFRP (data are represented as the mean \pm SD). (c) Toughness of KFRP-15% at different tensile rates. (d) Schematic diagram of the coupled damage-plasticity model. (e) The fitting strain-stress curves compared with experimental results.

A coupled damage-plasticity model was developed (Fig. S3(d)). The total macro axial strain was separated into the elastic and plastic parts, as expressed in the following incremental form:

$$d\epsilon_x = d\epsilon_x^e + d\epsilon_x^p = \frac{d\sigma_x}{(1-D)E_0} + d\epsilon_x^p \quad (1)$$

$$D = 1 - \frac{E}{E_0} \quad (2)$$

where ϵ_x and σ_x represented the axial strain and stress, respectively. ϵ_x^e was the elastic strain, and ϵ_x^p was the plastic strain. Subscript x referred to the loading direction. D indicated the damage variable. E_0 and E were the elastic modulus of virgin and

damaged material, respectively. Utilizing the associated flow rule [1], the incremental plastic strain $d\varepsilon_{ij}^p$ was obtained as:

$$d\varepsilon_{ij}^p = d\lambda \frac{\partial f}{\partial \sigma_{ij}} \quad (3)$$

in which $d\lambda$ was a proportionality factor, σ_{ij} denoted the stress in the principal material directions and f expressed the plastic potential function. Various plastic potential functions have been proposed for plastic models and the effective stress $\bar{\sigma}$ was defined as

$$\bar{\sigma} = f \quad (4)$$

According to the literatures [2, 3], the relationship between effective stress and effective plastic strain $\bar{\varepsilon}_p$ could be presented as a power law:

$$\bar{\varepsilon}_p = A(\bar{\sigma})^n \quad (5)$$

And the proportionality coefficient can be written as:

$$d\lambda = d\bar{\varepsilon}_p \quad (6)$$

Thus, by substituting Eq. (4) (5) (6) into Eq. (3):

$$d\varepsilon_{ij}^p = An(\bar{\sigma})^{n-1} d\bar{\sigma} \frac{\partial \bar{\sigma}}{\partial \sigma_{ij}} \quad (7)$$

where A and n indicated parameters to be determined from experimental results. Additionally, the Weibull function was introduced to describe the progressive modulus degradation in composites, which was expressed as [4]:

$$D(\bar{\sigma}) = 1 - \exp\left[-\left(\frac{\bar{\sigma}}{\sigma_e}\right)^{n_e}\right] \quad (8)$$

The parameters σ_e and n_e were decided by numerical fitting of experimental data. Therefore, the nonlinear constitutive model for KFRP under tensile loading was

determined as:

$$d\varepsilon_x = \frac{d\sigma_x}{E_0 \exp[-(\frac{\bar{\sigma}}{\sigma_e})^{n_e}]} + An(\bar{\sigma})^{n-1} d\bar{\sigma} \frac{\partial \bar{\sigma}}{\partial \sigma_x} \quad (9)$$

Besides, in the present study, the effective stress $\bar{\sigma}$ was adopted as:

$$\bar{\sigma} = \beta \sigma_x \quad (10)$$

where β represented the plasticity parameter. Finally, the nonlinear coupled damage-plasticity model was also established by putting formula (10) into formula (9) and integrating:

$$\varepsilon_x = \frac{\sigma_x}{E_0 \exp[-(\frac{\beta \sigma_x}{\sigma_e})^{n_e}]} + A(\sigma_x)^n \beta^{n+1} \quad (11)$$

The fitting parameters of KFRP in vertical type were listed in table S1.

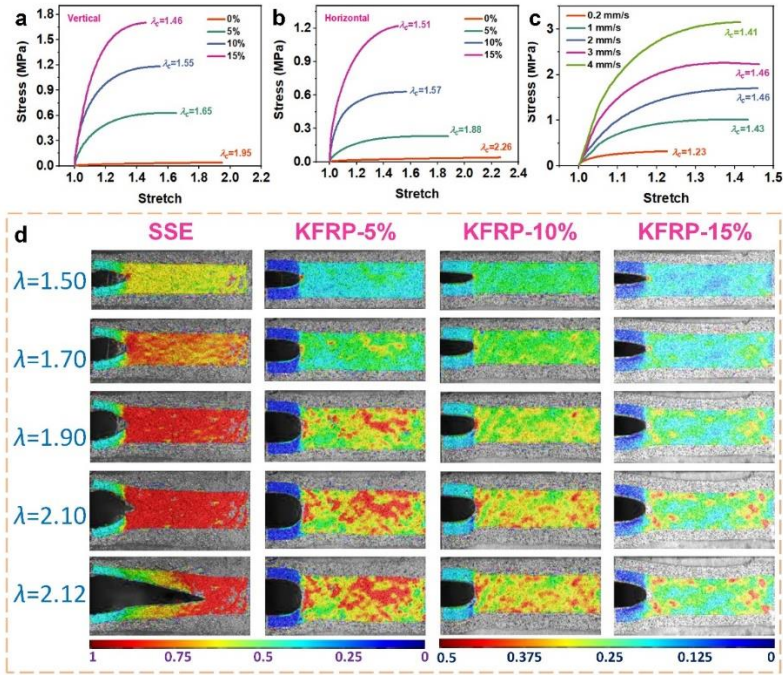


Fig. S4. The stress-stretch curves of unnotched KFRP whose fibers were (a) vertical and (b) horizontal before λ_c value at a speed of 2 mm/s. (c) The stress-stretch curves of unnotched KFRP-15% with vertical fibers orientation at different tensile rates. (d) The

lagrange strain ε_{yy} contour of vertical type KFRP.

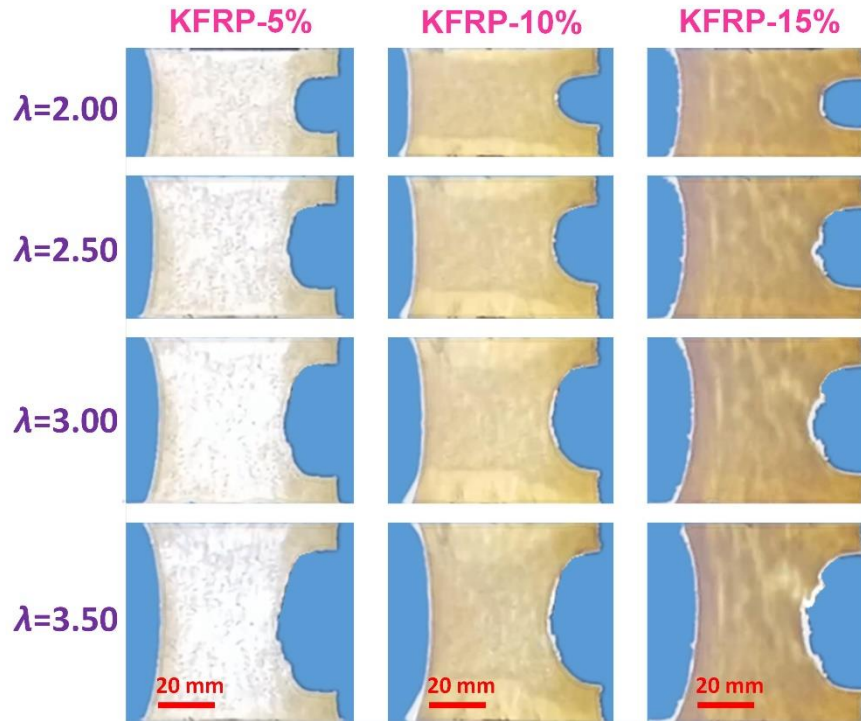


Fig. S5. The digital photos of KFRP under crack propagation experiment.

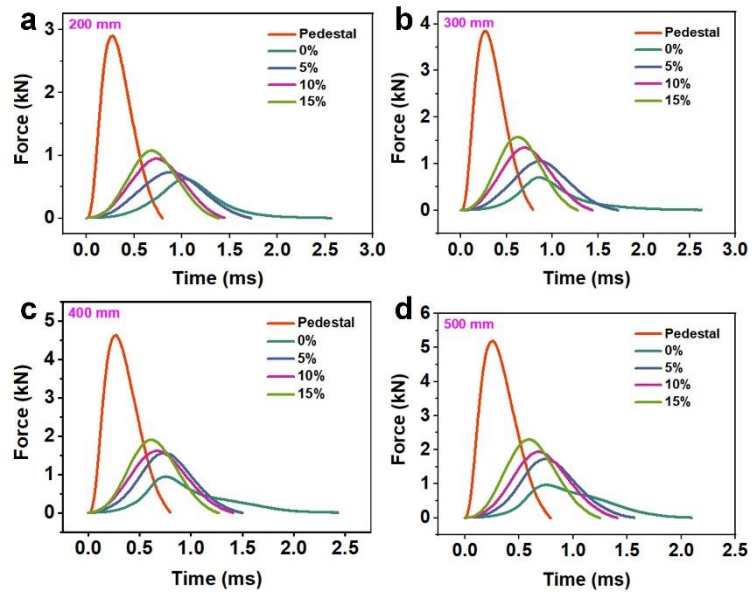


Fig. S6. The impact force of KFRP vs. time by dropping from (a) 200 mm, (b) 300 mm,

(c) 400 mm and (d) 500 mm.

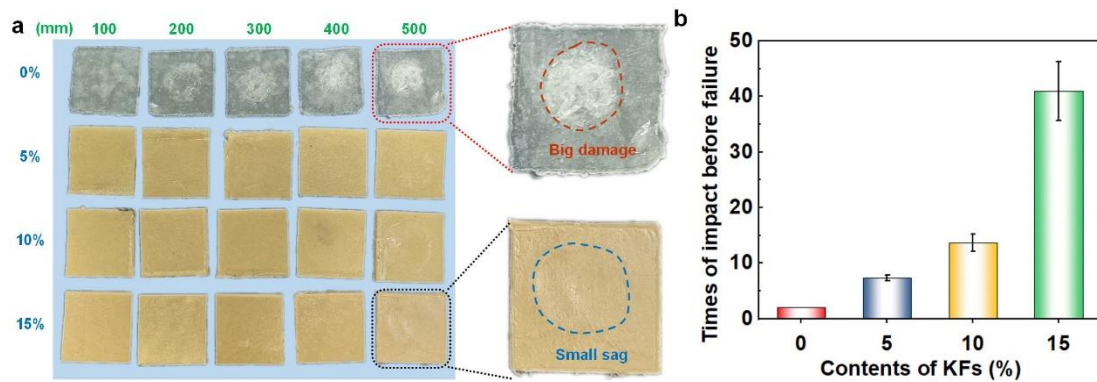


Fig. S7. (a)The photographs of KFRP after once dropping hammer impact. (b) The times of impact before KFRP failure (data are represented as the mean \pm SD).

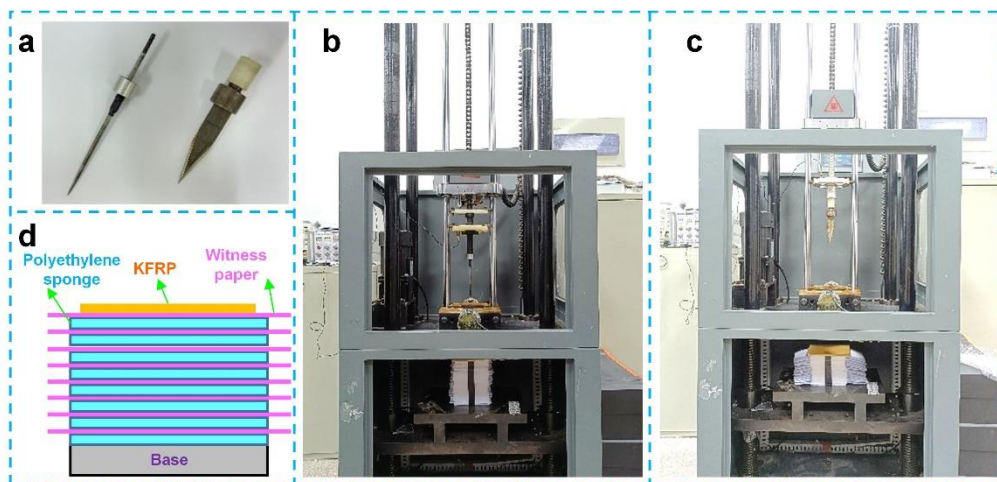


Fig. S8. (a) Image of the spike impactor and knife impactor. The pictures of the drop tower impact device when (b) spike punching and (c) knife cutting. (d) Schematic illustration of the stab resistance test KFRP and backing material.

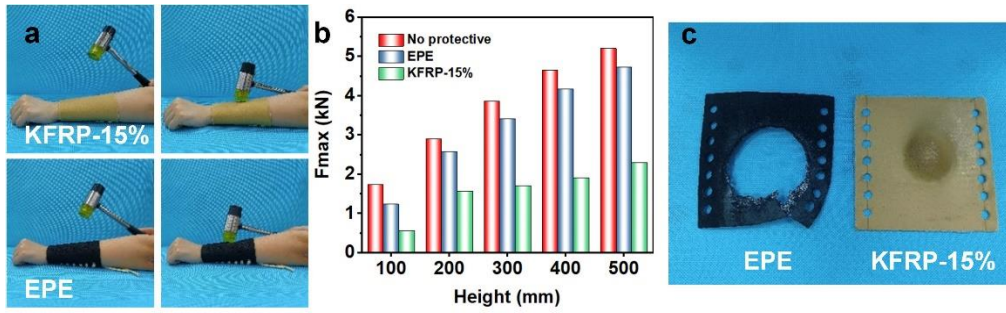


Fig. S9. (a) Photographs of the bracers based on KFRP-15% and EPE subjected to heavy hammer impact. (b) Comparison of F_{max} of KFRP-15% and EPE. (c) Photos of KFRP-15% and EPE after burning.

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- [2] Xie J, Fang G, Chen Z and Liang J. Modeling of Nonlinear Mechanical Behavior for 3D Needled C/C-SiC Composites Under Tensile Load. *Appl Compos Mater*, **2016**, 23: 783-797.
- [3] Zhai Z, Jiang B and Drummer D. Temperature-dependent response of quasi-unidirectional E-glass fabric reinforced polypropylene composites under off-axis tensile loading. *Compos B Eng*, **2018**, 148: 180-187.
- [4] Liu M, Li Y, Xu F, Xu Z and Cheng L. Dynamic compressive mechanical properties and a new constitutive model of 2D-C/SiC composites. *Mater Sci Eng A*, **2008**, 489: 120-126.