涂覆聚脲涂层的纤维增强树脂基复合材料板减振抗冲击性能研究

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摘要 本文分别建立了用于振动和冲击特性分析的涂覆聚脲涂层的纤维增强树脂基复合材料板的两类动力学模型, 并对涂层-复合材料板结构的减振和抗冲击性能同时进行了量化评估. 采用一阶剪切变形理论表示结构系统的位移场, 通过Rayleigh-Ritz法求解固有频率, 并通过振型叠加法获得脉冲激励下的振动响应, 进一步通过傅里叶变换和卷积运算推导获得了评价抗振性能的关键指标“动刚度”; 另外, 在考虑低速冲击造成的结构变形基础上, 建立了等效的二自由度弹簧-质量模型来描述其动态冲击过程与接触力的变化. 同时, 使用线性化赫兹接触理论获取冲击接触力, 并通过Runge-Kutta法求解冲击响应, 进而获得了评价抗冲击性能的关键数据“载荷-位移曲线”. 最后, 以有、无聚脲涂层的T300碳纤维/环氧树脂基复合材料板为研究对象, 搭建了振动与冲击一体化测试系统, 获得了有、无涂层试件的多项动力学参数, 验证了理论分析模型及其预测结果的正确性. 研究表明, 敷聚脲涂层后, 复合材料板试件的前四阶动刚度最大提升了74.7%, 且载荷-位移曲线上的冲击接触力和位移峰值分别下降了13.9%和13.3%, 有效证明了聚脲涂层在结构减振和抗冲击性能方面发挥的积极贡献.

关键词 聚脲涂层, 纤维增强, 复合材料板, 减振, 抗冲击

1 引言

目前, 具有轻质、高强特点的纤维/树脂基复合材料板被广泛应用于航空、航天、船舶、兵器工业等重要领域^[1~3]. 由于不可避免地工作在大幅振动、高强噪声、突发冲击等恶劣工况下, 导致纤维/树脂复合板容

易产生纤维断裂、基体开裂、分层损伤等缺陷^[4~6]. 聚脲弹性体作为一种新型的聚合物材料, 具有成本低、密度小、耐腐蚀性能好等优点^[7], 而且可以在金属或非金属表面形成良好的附着力^[8]. 随着研究的深入, 人们发现若使用聚脲材料作为涂层, 对各类型板结构的表面进行涂覆处理, 还可提高其抗冲击、耐疲劳等性能^[9,10].

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Li H, Wang D S, Zu X D, et al. Research on vibration and impact-resistant performances of fiber reinforced resin matrix composite plates with polyurea coating (in Chinese). Sci Sin Tech, 2021, 51: 959–969, doi: 10.1360/SST-2020-0419

目前, 在研究聚脲涂层-结构的振动、冲击等动力学问题时, 绝大部分文献都局限在各向同性的金属结构上. 例如, Feaga^[11]研究了弹丸速度对聚脲涂层RHA板在弹道冲击下性能的影响, 发现在受到高速冲击时(869 m/s), 聚脲的抗冲击效果显著下降. Amini和Nemat-Nasser^[12]通过有限元方法研究了聚脲涂层对钢板在受到冲击载荷时抗裂性能的影响, 有限元模拟结果表明, 无论是在正面还是背面, 聚脲涂层的存在都会阻碍裂纹的发育和扩展. Xue等人^[13]研究了不同形状的弹丸对钢板结构的高速冲击性能, 实验结果表明在钢板的背面涂敷聚脲涂层, 可更好地吸收尖头弹丸造成的冲击损伤. Roland等人^[14]研究了弹丸冲击下涂敷聚脲涂层的金属板的抗冲击特性, 发现涂层性能与基体的机械性能相互耦合, 在一定范围内金属板硬度越高、厚度越薄, 结构系统抗冲击性能越好. Mohotti等人^[15,16]采用有限元和实验方法研究了低、高速弹丸冲击下聚脲涂层-铝板的塑性变形, 通过与未涂层数据进行比较, 验证了涂层的抗冲击效果. 邓希旻等人^[17]对纯铝板和聚脲-铝板等结构开展了冲击实验, 发现将聚脲涂层涂覆在受冲击侧, 可有效缓解应力集中现象, 并提高结构的抗剪切能力. 张鹏等人^[18]测试了高硬度聚脲涂层-钢板结构的抗侵彻性能, 分析了无涂层、迎弹面涂层、背弹面涂层与双面涂层4种涂覆类型对钢板抗冲击性能的影响.

另有少量文献报道了聚脲涂层-纤维增强复合材料结构的动力学研究成果. 例如, Tekalur等人^[19]利用激波管对聚脲和玻璃纤维复合材料的涂层和夹层结构的抗冲击性能进行了实验研究, 发现在冲击面上涂敷聚脲层可有效提高抗冲击性. LeBlanc等人^[20]对涂覆聚脲涂层的玻璃纤维/乙烯基酯复合材料板在水下的爆炸响应进行了实验和数值模拟, 结果表明增大涂层厚度可降低复合板的瞬态冲击响应. 贺红鹰等人^[21]通过简支梁摆锤冲击实验, 测试了带有聚脲涂层的玻璃纤维增强材料的抗冲击性能, 发现聚脲涂层可提高结构抗冲击性能.

从上述文献调研可知, 目前人们对涂覆聚脲涂层的复合材料结构减振问题的研究鲜有报道, 且同时研究该类型结构振动与冲击问题的文献也非常少见. 为了解决上述问题, 本文在理论建模和实验测试的基础上, 以涂覆聚脲涂层(polyurea coating, PC)的纤维增强复合材料板(fiber-reinforced composite plate, FRCP)为

例, 对PC-FRCP结构的减振和抗冲击性能同时开展了研究, 并客观评估了涂层后结构系统的减振抗冲击性能. 本文所采用的理论评估与实验技术, 可为带涂层复合材料板壳结构的减振抗冲击性能研究, 提供理论与实践的参考.

2 减振性能分析

2.1 振动分析模型

假设聚脲涂层被均匀地涂覆在FRCP结构的两侧, 图1给出了PC-FRCP结构在脉冲载荷 $F(x, y, t)$ 作用下的振动分析模型. 在其中面建立参考平面和 xoy 坐标系, 并定义板长为 a , 宽为 b , 聚脲涂层厚度为 h_2 , 纤维增强层厚度为 h_1 , 总厚度为 h , 纤维铺层数为 n , 纤维方向与整体坐标系 x 轴方向的夹角为 θ , 图中的1代表纤维纵向, 2代表纤维横向, 3代表垂直于1-2平面方向, 脉冲载荷的激振点位于 P_a , 响应点位于 P_b . 另外, 定义 E_p 为聚脲涂层的弹性模量, E_{f1} , E_{f2} 分别为纤维/树脂层中沿着纤维方向和垂直纤维方向的弹性模量, G_{f12} 、 G_{f13} 、 G_{f23} 为相应的剪切模量; μ_p 为聚脲层的泊松比, μ_{f1} 和 μ_{f2} 分别为沿着纤维方向和垂直纤维方向的泊松比; ρ_p 和 ρ_f 分别代表聚脲层和纤维增强层的密度.

2.2 位移场假设

为了考虑剪切变形的影响, 根据一阶剪切变形理论^[22], 可将PC-FRCP结构位移场表达为

$$\begin{aligned} u(x, y, z, t) &= u_0(x, y, t) + z\varphi(x, y, t), \\ v(x, y, z, t) &= v_0(x, y, t) + z\psi(x, y, t), \\ w(x, y, z, t) &= w_0(x, y, t), \end{aligned} \quad (1)$$

图1 (网络版彩图) PC-FRCP结构在脉冲载荷激励下的振动分析模型

Figure 1 (Color online) Vibration analysis model of the PC-FRCP structure subjected to pulse load.

式中, u, v, w 表示层合板上任意一点的位移; u_0, v_0, w_0 为中面内某一点在 x, y, z 方向上的位移; φ, ψ 为绕 y, x 轴方向上的转角, t 为时间.

由于PC-FRCP结构对称, 弯曲运动与拉伸运动不耦合, u_0 和 v_0 可以忽略^[23]. 在已知层合板位移表达式的情况下, 可得相应的应变表达式为

$$\begin{cases} \varepsilon_x = \frac{\partial u}{\partial x} = z\varphi_{,x}; \varepsilon_y = \frac{\partial v}{\partial y} = z\psi_{,y}; \varepsilon_z = \frac{\partial w}{\partial z} = 0, \\ \gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = z(\varphi_{,y} + \psi_{,x}), \\ \gamma_{yz} = k_x \cdot \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) = k_x \cdot (\psi + w_{,y}), \\ \gamma_{xz} = k_x \cdot \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right) = k_x \cdot (\varphi + w_{,x}), \end{cases} \quad (2)$$

式中, k_x 为剪切修正系数, $k_x = \pi^2/12$.

假设PC-FRCP结构处于四边夹紧的约束边界, 则其位移场函数需满足以下条件:

$$\begin{aligned} w(0, y, t) = w(a, y, t) = w(x, 0, t) = w(x, b, t) = 0, \\ \frac{\partial w}{\partial x}(0, y, t) = \frac{\partial w}{\partial x}(a, y, t) = \frac{\partial w}{\partial y}(x, 0, t) \\ = \frac{\partial w}{\partial y}(x, b, t) = 0, \end{aligned} \quad (3)$$

$$\varphi(0, y, t) = \varphi(a, y, t) = \psi(x, 0, t) = \psi(x, b, t) = 0.$$

根据Ritz法^[24], 将位移表达式假设为

$$\begin{aligned} \varphi &= \sum_{m=1}^M \sum_{n=1}^N \alpha_{mn} P_m(\xi) P_n(\eta) \sin(\omega t), \\ \psi &= \sum_{m=1}^M \sum_{n=1}^N \beta_{mn} P_m(\xi) P_n(\eta) \sin(\omega t), \\ w_0 &= \sum_{m=1}^M \sum_{n=1}^N \gamma_{mn} P_m(\xi) P_n(\eta) \sin(\omega t), \end{aligned} \quad (4)$$

式中, $\alpha_{mn}, \beta_{mn}, \gamma_{mn}$ 是待定系数; $P_m(\xi)$ 和 $P_n(\eta)$ 是PC-FRCP结构的振型函数; ω 是固有圆频率; M, N 为通过Ritz法截取的项数 (为达到足够的计算精度通常取 $M=N=8$)^[25].

通过对满足边界条件的多项式簇首项进行Schmidt正交化处理可获得下列振型函数

$$\begin{aligned} P_1(\xi) &= \chi(\xi), \quad P_1(\eta) = \kappa(\eta), \\ P_2(\xi) &= (\xi - B_2)P_1(\xi)\xi, \\ P_k(\xi) &= (\xi - B_k)P_{k-1}(\xi) - C_k P_{k-2}(\xi), \\ \xi &= \xi, \eta, \quad k > 2, \end{aligned} \quad (5)$$

其中, B_k 和 C_k 为系数函数, 其表达式分别为

$$\begin{aligned} B_k &= \frac{\int_0^1 W(\zeta) [P_{k-1}(\zeta)]^2 d\zeta}{\int_0^1 W(\zeta) [P_{k-1}(\zeta)]^2 d\zeta}, \\ C_k &= \frac{\int_0^1 W(\zeta) P_{k-1}(\zeta) P_{k-2}(\zeta) d\zeta}{\int_0^1 W(\zeta) [P_{k-2}(\zeta)]^2 d\zeta}, \quad \zeta = \xi, \eta, \end{aligned} \quad (6)$$

式中, $W(\zeta)$ 是权函数, 通常取 $W(\zeta) = 1$. 假设结构处于四边固支边界条件, 则多项式 $\chi(\xi)$ 和 $\kappa(\eta)$ 的表达式为

$$\begin{aligned} \chi(\xi) &= \xi^2(1-\xi)^2, \quad \kappa(\eta) = \eta^2(1-\eta)^2, \\ \xi &= x/a, \quad \eta = y/b. \end{aligned} \quad (7)$$

2.3 固有特性求解

假设PC-FRCP结构的本构关系表达式如下:

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & & & \\ Q_{12} & Q_{22} & & & \\ & & Q_{44} & & \\ & & & Q_{55} & \\ & & & & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{bmatrix}, \quad (8)$$

式中, 对于聚脲弹性体而言,

$$\begin{aligned} Q_{11} &= Q_{22} = \frac{E_p}{1-\mu_p}, \\ Q_{12} &= \frac{\mu_p E_p}{1-\mu_p}, \\ Q_{44} &= Q_{55} = Q_{66} = \frac{E_p}{2(1+\mu_p)}. \end{aligned}$$

引入坐标转换矩阵 Γ :

$$\Gamma = \begin{bmatrix} c^2 & s^2 & 0 & 0 & -2cs \\ s^2 & c^2 & 0 & 0 & 2cs \\ 0 & 0 & c & s & 0 \\ 0 & 0 & -s & c & 0 \\ cs & -cs & 0 & 0 & c^2 - s^2 \end{bmatrix}, \quad (9)$$

其中,

$$c = \cos\theta_k, \quad s = \sin\theta_k, \quad (10)$$

式中, k 表示纤维层的第 k 层, θ_k 表示第 k 层的纤维方向与整体坐标系 x 轴的夹角.

进一步, 可得PC-FRCP结构中纤维层对应的偏轴应力-应变关系:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{Bmatrix}^k = \mathbf{\Gamma} \begin{bmatrix} Q_{11} & Q_{12} & 0 & 0 & 0 \\ Q_{12} & Q_{22} & 0 & 0 & 0 \\ 0 & 0 & Q_{44} & 0 & 0 \\ 0 & 0 & 0 & Q_{55} & 0 \\ 0 & 0 & 0 & 0 & Q_{66} \end{bmatrix} \mathbf{\Gamma}^T \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{Bmatrix}^k, \quad (11)$$

其中,

$$Q_{11} = \frac{E_{f1}}{1 - \mu_{f1}\mu_{f2}}, Q_{12} = Q_{21} = \frac{\mu_{f1}E_{f2}}{1 - \mu_{f1}\mu_{f2}} = \frac{\mu_{f2}E_{f1}}{1 - \mu_{f1}\mu_{f2}}, \quad (12)$$

$$Q_{22} = \frac{E_{f2}}{1 - \mu_{f1}\mu_{f2}}, Q_{44} = G_{f23}, Q_{55} = G_{f13}, Q_{66} = G_{f12}.$$

可将图1所示的上、下聚脲层和纤维层的动能 T_{p1} , T_{p2} , T_f 和应变能 U_{p1} , U_{p2} , U_f 表示为

$$T_{p1} = \frac{1}{2} \int_A \int_{h_1/2}^{h/2} \rho_p \left[\left(\frac{\partial u}{\partial t} \right)^2 + \left(\frac{\partial v}{\partial t} \right)^2 + \left(\frac{\partial w}{\partial t} \right)^2 \right] dz dA,$$

$$T_f = \frac{1}{2} \int_A \int_{-h_1/2}^{h_1/2} \rho_f \left[\left(\frac{\partial u}{\partial t} \right)^2 + \left(\frac{\partial v}{\partial t} \right)^2 + \left(\frac{\partial w}{\partial t} \right)^2 \right] dz dA, \quad (13)$$

$$T_{p2} = \frac{1}{2} \int_A \int_{-h/2}^{-h_1/2} \rho_p \left[\left(\frac{\partial u}{\partial t} \right)^2 + \left(\frac{\partial v}{\partial t} \right)^2 + \left(\frac{\partial w}{\partial t} \right)^2 \right] dz dA,$$

$$U_{p1} = \frac{1}{2} \int_A \int_{h_1/2}^{h/2} (\sigma_x \varepsilon_x + \sigma_y \varepsilon_y + \tau_{xy} \gamma_{xy} + \tau_{yz} \gamma_{yz} + \tau_{xz} \gamma_{xz}) dz dA,$$

$$U_f = \frac{1}{2} \int_A \int_{-h_1/2}^{h_1/2} (\sigma_x \varepsilon_x + \sigma_y \varepsilon_y + \tau_{xy} \gamma_{xy} + \tau_{yz} \gamma_{yz} + \tau_{xz} \gamma_{xz}) dz dA, \quad (14)$$

$$U_{p2} = \frac{1}{2} \int_A \int_{-h/2}^{-h_1/2} (\sigma_x \varepsilon_x + \sigma_y \varepsilon_y + \tau_{xy} \gamma_{xy} + \tau_{yz} \gamma_{yz} + \tau_{xz} \gamma_{xz}) dz dA.$$

将各层的动能和应变能相加, 可获得PC-FRCP结构总的动能 T 和应变能 U 为

$$T = T_{p1} + T_f + T_{p2}, \quad (15a)$$

$$U = U_{p1} + U_f + U_{p2}. \quad (15b)$$

将式(4)代入能量方程(15)中, 可获得用待定系数 α_{mn} , β_{mn} , γ_{mn} 表示的应变能和动能表达式. 则相应的最大应变能 $U_{\max}$ 和动能 $T_{\max}$ 可表示为

$$U_{\max} = \frac{1}{2} \mathbf{q}^T \mathbf{K} \mathbf{q}, \quad (16a)$$

$$T_{\max} = \frac{1}{2} \omega^2 \mathbf{q}^T \mathbf{M} \mathbf{q}, \quad (16b)$$

式中, $\mathbf{K}$ 和 $\mathbf{M}$ 分别为刚度矩阵和质量矩阵,

$$\mathbf{q} = (\alpha_{11}, \alpha_{12}, \dots, \alpha_{mn} \beta_{11}, \beta_{12}, \dots, \beta_{mn} \gamma_{11}, \gamma_{12}, \dots, \gamma_{mn})^T$$

为特征向量.

可定义Lagrange能量方程的表达式如下:

$$L = T_{\max} - U_{\max}. \quad (17)$$

利用Rayleigh-Ritz法求解PC-FRCP结构的固有特性问题, 即是求解使 L 有最小值的所有待定参数, 即有下式:

$$\left(\frac{\partial L}{\partial \alpha_{mn}}, \frac{\partial L}{\partial \beta_{mn}}, \frac{\partial L}{\partial \gamma_{mn}} \right) = 0 \quad m = 1, 2, \dots, M; \quad (18)$$

$$n = 1, 2, \dots, N.$$

将式(16)和(17)代入式(18)中, 可获得

$$(\mathbf{K} - \omega^2 \mathbf{M}) \mathbf{q} = 0. \quad (19)$$

为保证方程(19)有解, 需要系数矩阵的行列式为0, 即 $|\mathbf{K} - \omega^2 \mathbf{M}| = 0$. 这样就求得结构的固有频率, 将特征向量 $\mathbf{q}$ 代到式(4)中, 则可求得模态振型.

2.4 振动响应与动刚度求解

假设脉冲载荷 $F(x, y, t)$ 和结构振动响应 $X(t)$ 表达式分别为

$$F(x, y, t) = f(t) \delta(x - x_1) \delta(y - y_1),$$

$$f(t) = \begin{cases} f_0 \sin(\omega_f t), & 0 \leq t \leq t_1, \\ 0, & t > t_1, \end{cases} \quad (20)$$

$$X(t) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} W_{mn}(x, y) T_{mn}(t), \quad (21)$$

式中, (x_1, y_1) 为激励点坐标(对应激励点为 P_a), f_0 为激振力幅值, ω_f 为激励频率, t_1 为载荷作用的时间, $W_{mn}(x, y)$ 为模态振型, T_{mn} 为各阶振型分量.

参考文献[26,27], 若考虑阻尼的影响, 则PC-FRCP结构的振动微分方程可表示为

$$\frac{d^2 T_{mn}(t)}{dt^2} + 2\zeta_r \omega \frac{dT_{mn}}{dt} + (\omega)^2 T_{mn}(t) = \frac{P_{mn}(t)}{M_{mn}}, \quad (22)$$

式中, $P_{mn}(t)$ 和 M_{mn} 分别为结构的第 (m, n) 阶广义力和广义质量; ζ_r 为结构的第 r 阶模态阻尼比, 可通过实验测试获得.

在初始条件为零的情况下, 可用杜哈梅积分求解振动微分方程, 由此可得各阶振型分量:

$$T_{mn}(t) = \frac{W_{mn}(x_1, y_1)}{\omega_d M_{mn}} \cdot \int_0^t f(\tau) e^{-\zeta_r \omega(t-\tau)} \sin \omega_d(t-\tau) d\tau, \quad (23)$$

式中, ω_d 为有阻尼固有圆频率, 且 $\omega_d = \omega\sqrt{1-\zeta_r^2}$.

利用 Simpson 数值积分法求解式(23), 并将结果回代到振动响应式(21)中, 即可用振型叠加法求得脉冲激励作用下结构的时域振动响应.

进一步, 在已知脉冲振动响应时域表达式的情况下, 对其进行傅里叶变换 ($F[y]$) 和卷积运算 ($C_{on}[y_1 * y_2]$) 后, 即可得到 PC-FRCP 结构任一响应点 P_b 相对于激励点 P_a 的动刚度表达式

$$k_{ba}(\omega) = 1/F \left[\frac{W_{mn}(x_1, y_1)}{\omega M_{mn}} \int_0^t f(\tau) \sin \omega(t-\tau) d\tau \right]. \quad (24)$$

如此, 在获得的动刚度 $k_{ba}(\omega)$ 的基础上, 可利用该指标来评估结构系统的抗振性能.

3 抗冲击性能分析

3.1 冲击分析模型和冲击接触力求解

当 PC-FRCP 结构受到低速冲击时会产生结构变形, 参考文献[28]的相关假设, 在忽略材料损伤的基础上, 采用图2所示的冲击接触位移模型, 来表示冲击体与结构之间存在的相对位移 α . 另外, 假设 v 为冲击体速度, z_b 为层合板位移, z_i 为冲击体位移, t 为冲击作用时间.

参考文献[29]的线性化赫兹接触模型, 可获得线性化接触刚度表达式为

$$K_I = (2\pi m_i v f_i)^{1/3} \cdot \left[\frac{4}{3} \frac{R_i^{1/2}}{((1-\mu_i^2)/E_i) + ((1-\mu_j^2)/E_j)} \right]^{2/3}, \quad (25)$$

图2 冲击接触位移模型

Figure 2 Impact contact displacement model.

式中, m_i 为冲击体的质量; f_i 为 PC-FRCP 结构的第一阶固有频率; R_i , E_i , μ_i 分别为冲击体的半径、弹性模量和泊松比; μ_j 和 E_j 分别为结构的等效弹性模量和等效泊松比, 其表达式为^[30]

$$\begin{aligned} \mu_j &= 2 \cdot \mu_p (h_2/h) + \mu_{\text{c}} (h_1/h), \\ E_j &= h / [2 \cdot (h_2/E_p) + (h_1/E_{\text{c}})]. \end{aligned} \quad (26)$$

由此可得冲击作用下 PC-FRCP 结构接触力的表达式为

$$F(t) = K_I \alpha = K_I (z_i - z_b). \quad (27)$$

进一步, 将受到冲击载荷作用的 PC-FRCP 结构等效为弹簧质量模型, 采用二自由度弹簧-质量模型来确定冲击接触力, 模型如图3所示. 图中 K_b 为弯曲刚度, K_s 为剪切刚度, K_m 为层合板的膜刚度, m_b 为 PC-FRCP 结构质量.

由图3中的弹簧-质量模型, 可得

$$\begin{aligned} m_i \ddot{z}_i + F(t) &= 0, \\ m_b \ddot{z}_b + K_{bs} z_b + K_m z_b^3 - F(t) &= 0, \end{aligned} \quad (28)$$

式中, 弯-剪刚度 K_{bs} 的计算公式为

$$K_{bs} = m_b (2\pi f_i)^2. \quad (29)$$

由于膜刚度 K_m 在聚合物复合材料中较低, 因此可忽略不计. 将式(27)代入式(28)中, 可获得该模型的运

图3 考虑冲击载荷作用的弹簧-质量模型

Figure 3 Spring-mass model subjected to impact load.

中, 利用模态力锤对结构进行脉冲激励, 并通过轻质加速度传感器来获得振动响应信号, 在获得频响函数数据后, 可通过半功率带宽法获得有、无涂层FRCP试件前4阶阻尼比分别为1.07%, 0.85%, 0.95%, 1.04%和0.95%, 0.80%, 0.88%, 0.93%. 此外, 脉冲激励点 $P_a(x_1, y_1)=(50, 50)$, 响应点 $P_b(x_2, y_2)=(121, 100)$, 冲击激励点 $P_{im}(x_3, y_3)=(85.5, 110)$.

4.2 对比分析与减振抗冲击性能评价

图5给出了有、无涂层FRCP试件对应的冲击面和非冲击面的实验照片. 从图中可以看出在涂敷涂层后, 冲击面的损伤面积小幅减小, 而非冲击面的损伤面积明显减小. 图6分别给出了实验与计算获得的有、无涂层FRCP试件的激振力和振动响应的时域波形以及前4阶动刚度曲线. 另外, 图7为通过两种方式获得的有、无涂层试件的接触力和位移响应的时域波形以及载荷-位移曲线.

对上述数据进行分析可知, 理论计算与测试获得的时域振动响应吻合较好, 且有、无涂层结构系统固有频率的最大计算误差 $R_{f_{re}}$ 为4.2%, 动刚度的最大计算误差 R_k 为9.3%, 进而验证了振动性能分析结果的正确

图5 有、无涂层时FRCP结构的冲击实验照片. (a) 冲击前; (b) 冲击后

Figure 5 Impact test photos of the FRCP structures with and without coating. (a) Before impact; (b) after impact.

性. 同时, 对相关的冲击数据进行比较可知, 理论预测与实验获得的动态冲击接触力、冲击位移以及载荷-位移曲线的变化趋势吻合较好. 其中, 接触力峰值的最大计算误差 R_f 为7.0%, 冲击位移峰值的最大计算误差 R_d 为8.6%. 误差在允许范围之内, 由此验证了冲击性能分析结果的正确性. 但仍有必要对上述计算结果的误差原因进行分析, 动刚度计算误差可能是由于在计算过程中输入的尺寸、材料参数与实际情况有偏差,

图6 (网络版彩图)实验与计算获得的FRCP ((a)~(c))和PC-FRCP ((d)~(f))结构振动参数. (a), (d) 激振力波形; (b), (e) 响应波形; (c), (f) 动刚度

Figure 6 (Color online) The vibration parameters of the FRCP ((a)~(c)) and PC-FRCP ((d)~(f)) structures obtained by tests and calculations. (a), (d) Time domain excitation force; (b), (e) time domain response; (c), (f) dynamic stiffness.

图 7 (网络版彩图)实验与计算获得的FRCP ((a)~(c))和PC-FRCP ((d)~(f))结构冲击参数. (a), (d) 接触力波形; (b), (e) 冲击响应波形; (c), (f) 载荷-位移曲线

Figure 7 (Color online) The impact parameters of the FRCP ((a)~(c)) and PC-FRCP ((d)~(f)) structures obtained by tests and calculations. (a), (d) Time domain impact contact force; (b), (e) time domain impact response; (c), (f) load-displacement curve.

表 1 有、无聚脲涂层FRCP结构的动刚度、冲击接触力和冲击位移峰值

Table 1 Dynamic stiffness, contact force and impact displacement peak value of the FRCP structures with and without polyurea coating

类型	载荷-位移曲线		动刚度曲线			
	接触力峰值 (N)	冲击位移峰值 (mm)	1阶动刚度 (N/m)	2阶动刚度 (N/m)	3阶动刚度 (N/m)	4阶动刚度 (N/m)
FRCP (A)	1696	11.64	2.463×10^4	5.526×10^4	1.409×10^5	7.393×10^4
PC-FRCP (B)	1461	10.09	4.048×10^4	9.653×10^4	1.563×10^5	1.152×10^5
变化率((B-A)/A) (%)	-13.9	-13.3	64.4	74.7	10.9	55.8

且计算模拟的激激励力与实测结果也存在一定的偏差; 另外, 冲击计算误差也不可避免的存在, 这是由于被测结构与落锤冲击冲击接触过程是极其复杂的, 本文仅采用线性化赫兹接触理论来近似求解冲击接触力, 且对冲击造成的损伤模式进行了简化处理.

另外, 为了量化评估聚脲涂层对FRCP结构在减振和抗冲击性能上的贡献, 以理论计算结果为例, 表1给出了有、无聚脲涂层FRCP结构的动刚度和冲击接触力、冲击位移峰值结果. 对其进行分析可知, 涂敷聚脲涂层后, 前四阶动刚度提升程度在10.9%~74.7%之间, 且载荷-位移曲线上的冲击接触力峰值下降了13.9%, 冲击位移峰值下降了13.3%. 由此可知, 聚脲涂层确实

可提升FRCP结构的减振和抗冲击性能.

5 结论

本文分别提出了PC-FRCP结构振动和冲击两类动力学模型来评估其减振抗冲击性能, 并基于自行设计的振动和冲击一体化实验系统开展了实验验证研究, 得到如下结论.

(1) 理论预测和测试获得的有、无聚脲涂层FRCP结构的减振抗冲击性能参数吻合良好. 其中, 动刚度计算误差最大不超过9.3%, 且载荷-位移曲线上的冲击位移或接触力峰值的最大计算误差不超过8.6%, 由此证

明了所提出的理论模型的正确性和有效性.

(2) 实测结果表明, 涂敷聚脲涂层后, 结构前四阶动刚度最大提升了74.7%, 且载荷-位移曲线上的冲击

接触力和位移峰值分别下降了13.9%和13.3%. 由此可证明, 聚脲涂层可同时对FRCP结构的抗振动和抗冲击性能发挥积极贡献.

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Research on vibration and impact-resistant performances of fiber reinforced resin matrix composite plates with polyurea coating

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In this paper, two types of dynamic models for vibration and impact analyses of the fiber-reinforced resin matrix composite plates with polyurea coating are established, respectively. Also, the vibration and impact resistant performances of the coating-composite plate structures are evaluated quantitatively. For one thing, the first-order shear deformation theory is adopted to represent the displacement field of the structural system, and the natural frequency is solved by the Rayleigh-Ritz method. Meanwhile, the vibration response subjected to impulse excitation is achieved by the mode superposition method, and the key index “dynamic stiffness” for evaluating the vibration resistant performance is obtained by the Fourier transform and convolution calculation operations. For another thing, with consideration of the structural deformation affected by the low velocity impact, an equivalent two-degree-of-freedom spring-mass model is established to describe the dynamic impact process and the change of contact force. Meanwhile, the linearized Hertz contact theory is utilized to obtain the impact contact force. After the impact response is solved by the Runge-Kutta method, the key data “load-displacement curve” for evaluating impact resistant property is further obtained. Finally, by taking T300 carbon fiber/epoxy-based composite plate specimens with and without polyurea coating materials as the research objects, an integrated vibration and impact test system is set up. Several dynamic parameters of those specimens with and without coating are obtained, which validate the theoretical analysis models as well as their prediction results. The research results indicate that after the polyurea coating is applied, the first four dynamic stiffness values of the composite plate specimens are increased with the maximum rising degree of 74.7%, and the impact contact forces and displacement peak values of the load-displacement curves are reduced by 13.9% and 13.3%, respectively. Hence, the contribution of polyurea coating to the effects of vibration suppression and impact resistance of the structure system has been effectively verified.

polyurea coating, fiber-reinforced, composite plate, vibration reduction, impact resistance

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