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钢筋混凝土结构锈蚀特征的漏磁探测研究进展

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摘要: 以混凝土结构中钢筋锈蚀特征的漏磁探测技术为主线,对相关研究进行综合回顾与分析.结果表明,基于漏磁探测技术能够准确识别混凝土结构中钢筋的锈蚀区域并定量评估钢筋锈蚀率.为进一步提升利用漏磁技术探测既有钢筋混凝土结构锈蚀特征的适用性和准确性,未来还需要充分考虑磁化强度随机分布引起的锈蚀率评估结果的概率分布特性,明确应力、疲劳、箍筋/相邻纵筋、锈蚀产物和混凝土的影响,推动基于漏磁成像的计算机视觉自动识别和融合多指标、多技术方法的应用.

关键词: 钢筋混凝土结构;漏磁探测;锈蚀率;定量评估;概率化

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State-of-the-Art on Magnetic Flux Leakage Detection of Corrosion Characteristics of Reinforced Concrete Structures

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Abstract: The main focus is the state-of-the-art magnetic flux leakage (MFL) detection technique for rebar corrosion characteristics in reinforced concrete (RC) structures, providing a comprehensive analysis of relevant research. The results indicate that the MFL detection technique can accurately identify corrosion areas of rebar embedded in RC structures and quantitative assessment the corrosion degree of the rebar. To further improve the applicability and accuracy of using the MFL detection technique for corrosion characteristics in existing RC structures, the probabilistic distribution characteristics of corrosion degree assessments resulting from the random distribution of magnetization should be fully considered, the effects of stress, fatigue, stirrups/adjacent longitudinal rebars, corrosion products, and concrete should be clarified, and the application of computer vision for automatic identification based on MFL imaging and the integration of multiple indicators and methodologies needed be promoted.

Key words: reinforced concrete structure; magnetic flux leakage detection; corrosion degree; quantitative assessment; probability

混凝土结构广泛应用于桥梁、建筑和隧道等基础设施[1-2].在荷载与环境共同作用下,混凝土中的钢筋发生锈蚀[3-4],引起钢筋截面减小,钢-混黏结退化,保护层开裂[5],导致结构受力性能退化,可靠性降低[6-7],甚至提前遭到破坏,从而造成巨大生命财产损失.及时发现并准确测定混凝土中钢筋锈蚀的发生和发展,对保障结构全寿命安全具有重要意义.

受相对湿度、含氧量和材料特性等影响,混凝土结构中的锈蚀过程随机性很强[8-12].钢筋锈蚀一般采用电化学和物理方法探测.其中,采用半电池电位等电化学

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方法[13-14]虽可获取钢筋真实的锈蚀状态或锈蚀速率，但很难测定锈蚀率 η. 采用声发射[15]、光纤传感[16]及红外热成像[17]等物理方法虽能够定性估计钢筋的锈蚀程度，但易受随机环境条件、材料特性和复杂锈蚀体系参数的干扰而无法量化 η. 虽然 X/γ 射线断层扫描[18]精确成像实现了对高精度 η 的探测，但放射污染、高成本和低效率限制了其工程应用. 与之相比，尽管涡流、探地雷达和漏磁等电磁法的评估精度尚有差距，但更加适用于工程应用. 其中漏磁法又以成本低、效率高和抗干扰能力强成为探测钢筋锈蚀的优选方法.

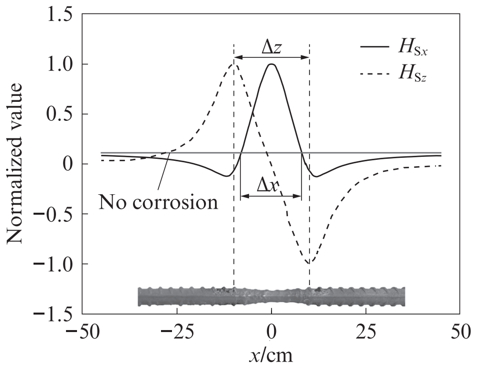
本文对基于漏磁法探测钢筋锈蚀研究的丰富成果进行整体回顾，以期发现关键问题，明确未来研究重点.

1　原理简述

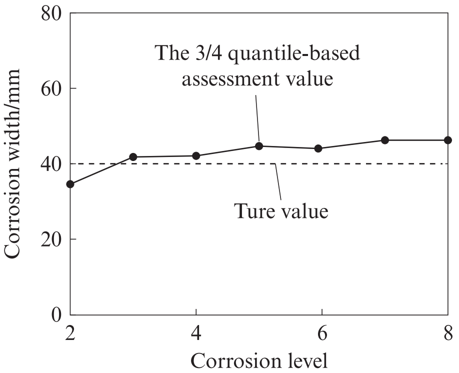
钢筋漏磁原理通常被描述为“铁磁构件被磁化后其内部会产生磁场，若构件上存在锈蚀等缺陷，磁场会泄漏到构件外部并形成漏磁场[19]”. 根据有无人工磁激励装置，钢筋漏磁可分为漏磁[20]和自发漏磁[5]两种形式. 两者物理本质一致，均可研究分析钢筋的锈蚀特征.

2　基于漏磁的钢筋锈蚀定位和锈蚀宽度评估

钢筋锈蚀可分为局部锈蚀和整体锈蚀. 图 1 为钢筋局部锈蚀的漏磁特征. 对于钢筋局部锈蚀，无论锈坑几何形态为 V 形[5]、半弧形[20-21]还是矩形[22-23]，均存在图 1(a)所示的漏磁曲线. 图 1(a)显示：钢筋的 2 个漏磁分量 H_{Sx} 和 H_{Sz} 的曲线在锈蚀区域出现明显畸变，且在局部锈蚀中点或边界处出现峰值，该特征已被广泛用于准确定位局部锈蚀[5, 20-53]；利用 H_{Sx} 曲线与 x 轴的交点间距 Δx 或 H_{Sz} 曲线的峰谷值间距 Δz 可以确定锈蚀宽度. 由图 1(b)可见，基于 Δx 实施的锈蚀宽度评估案例准确性较好[43]. 然而，Δx 和 Δz 会随着传感器与钢筋直线距离(提离高度)的增大而增加，从而影响锈蚀宽度估计的准确性. 因此，未来基于漏磁的锈蚀宽度评估还需要进一步考虑该影响. 此外，使用平面扫描数据可以对钢筋的局部锈蚀进行漏磁成像[34]，该方法准确性较高.



(a) MFL component



(b) Corrosion width assessment

图 1　钢筋局部锈蚀的漏磁特征

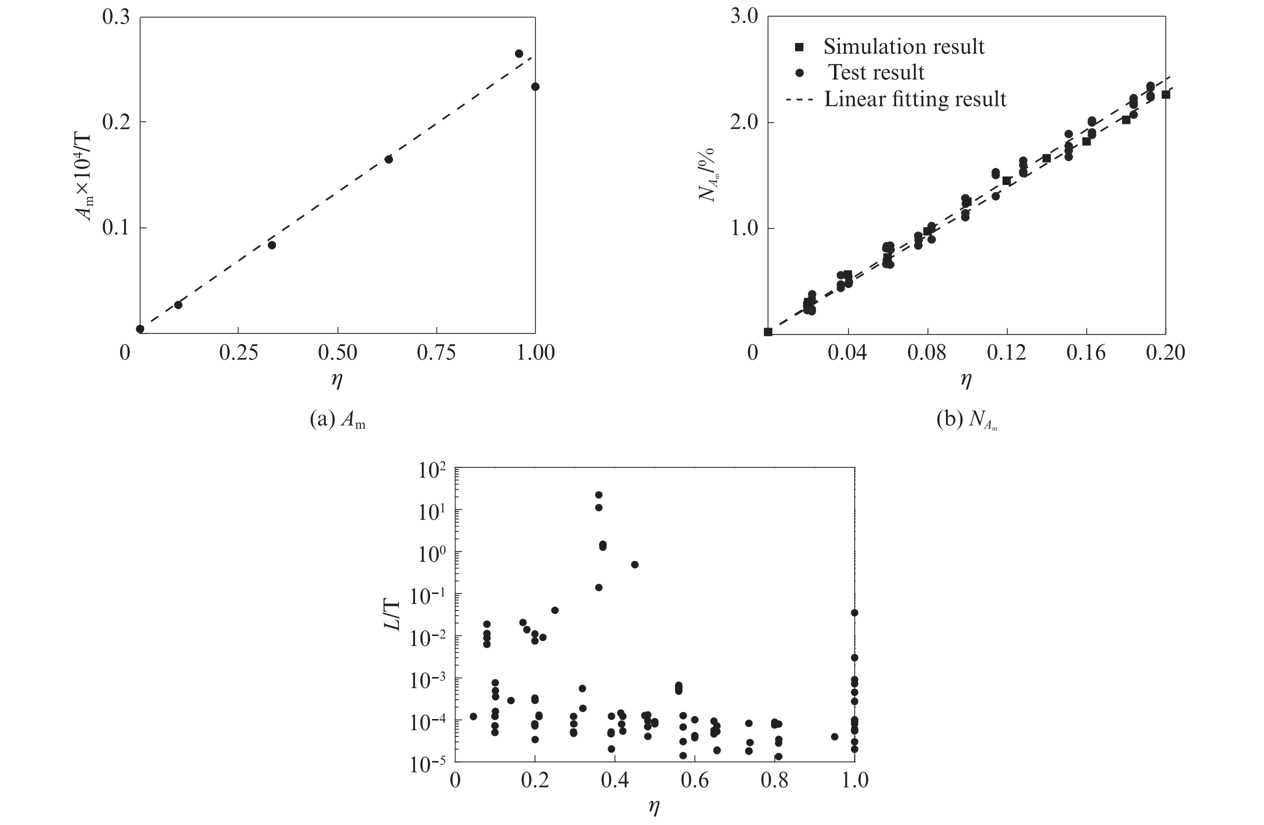
Fig. 1　MFL characteristics of rebar's local corrosion[5, 20-23, 43]

钢筋的整体锈蚀具有复杂的不均匀锈蚀形态，常用有限元仿真求解漏磁数值. 整体锈蚀钢筋的漏磁场变化包括两部分：一是截面积缩减造成的漏磁强度整体降低，二是不均匀锈蚀引起的漏磁场局部波动[54-56]. 总体上看，无论是局部锈蚀还是整体锈蚀，采用漏磁法探测钢筋锈蚀均是从分析漏磁场变化这一本质入手的.

3　基于漏磁的钢筋锈蚀率评估

3.1　钢筋锈蚀率的定性评估

确定钢筋锈蚀的位置和宽度后，需要确定的是钢筋锈蚀率 η. 大量理论和实践证明，钢筋锈蚀漏磁变幅 A_m 随着锈蚀深度 d 或 η 的增加而单调增加. 基于此，研究发现 A_m 与 η 线性相关[5,21,22,28-31,34,37,39,44,50,52,57-76]. 图 2 为钢筋锈蚀漏磁变幅 A_m(归一化漏磁变幅 N_{A_m})与锈蚀率 η 的典型线性关系及线性增长速率 L. 根据唯象理论，这种线性关系可以理解为一旦钢筋截面受到损失，其内部的磁力线就等比例“漏”到外部. 尽管该线性关系定性判断一致，但这些文献中 L 的最大差异接近 7 个数量级(图 2(c)). 这表明，不同钢筋试件在相同锈蚀率 η 下锈蚀漏磁变幅 A_m 差异巨大，故而仅根据 A_m 无法评估钢筋的 η. 根本原因在于磁化激励或自发磁化使得不同钢筋的磁化强度 $\boldsymbol{M}$ 大相径庭，进而导致 A_m 出现巨大差别.



(a) A_m (b) N_{A_m} (c) L

图2 钢筋锈蚀漏磁变幅(归一化漏磁变幅)与锈蚀率的典型线性关系及其线性增长速率

Fig. 2 Typical linear relationships between MFL variation amplitude (normalized MFL variation amplitude) and corrosion degree and linear growth rates[5,21,22,28-31,34,37,39,44,50,52,57-76]

3.2 基于概率的钢筋锈蚀率定量评估

如上所述,钢筋锈蚀漏磁变幅A_m本质上取决于锈蚀率η和磁化强度$\boldsymbol{M}$.为了基于A_m来定量评估钢筋的η,须消除钢筋在磁化强度$\boldsymbol{M}$上的差异,以便将“一个方程,两个未知数”的非唯一解问题转化为“一个方程,一个未知数”的唯一解问题.目前,基于钢筋感应磁场强度$\boldsymbol{H}_I$和自发漏磁场强度$\boldsymbol{H}_S$的“动态联动机制”,已经发展出一种针对钢筋局部锈蚀率η的无损量化评估方法[75].在理想的纵向均匀磁化假定条件下,此“动态联动机制”实质上是钢筋的$\boldsymbol{H}_I$和$\boldsymbol{H}_S$与$\boldsymbol{M}$的纵向分量M_x相关[75],其表达式如下:

$$\boldsymbol{H}_S=\frac{dM_x}{8\pi\mu_0}f_1(x,\ y,\ z,\ w,\ r) \tag{1}$$

$$\boldsymbol{H}_I=\frac{M_x}{8\pi\mu_0}f_2(x,\ y,\ z,\ l,\ r) \tag{2}$$

式中:$x,\ y,\ z$为空间坐标;w为1/2局部锈蚀宽度,mm;μ_0为真空磁导率,H/mm;l为1/2钢筋长度,mm;r为钢筋半径,mm.

研究发现,在$\boldsymbol{H}_S$和$\boldsymbol{H}_I$某一分量的曲线上分别取幅值、梯度或均值等简单几何参数T_1和T_2,将两者进行比值处理后得到量化指标I,其表达式[75]为:

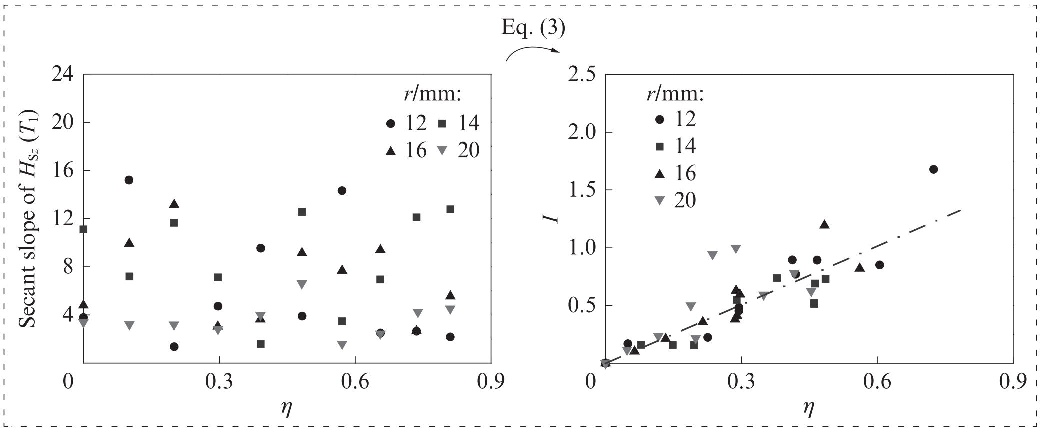
$$I=d\frac{T_1[f_1(x,\ y,\ z,\ w,\ r)]}{T_2[f_2(x,\ y,\ z,\ l,\ r)]}=df_3(x,\ y,\ z,\ w,\ l,\ r) \tag{3}$$

由式(3)可知,量化指标I的表达式中消除了M_x,取用不同的T_1和T_2将产生不同的I.采用40根具有不同磁化强度$\boldsymbol{M}$的局部锈蚀钢筋进行试验,其漏磁量化处理与锈蚀率分级评估结果见图3.

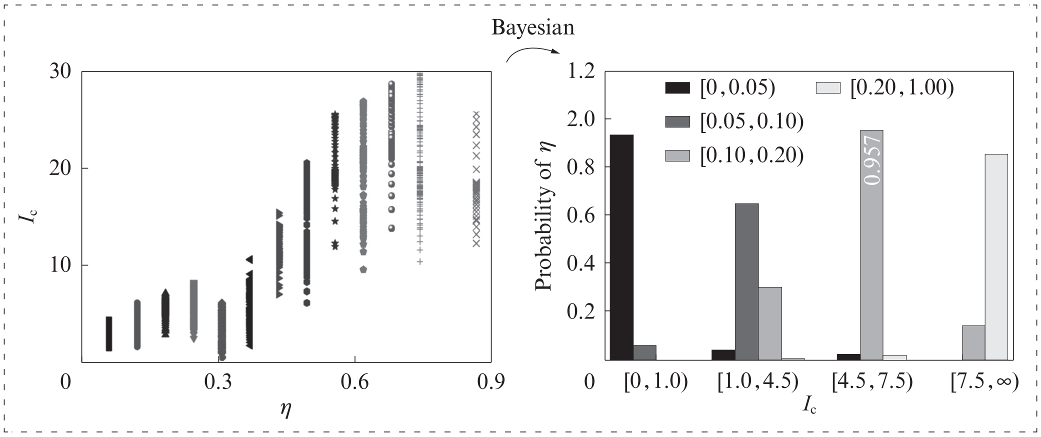
由图3(a)可见,40根局部锈蚀钢筋的H_{Sz}曲线的割线斜率T_1是随机分布的.根据式(3)可通过钢筋感应磁场法向分量H_{Iz}曲线的割线斜率T_2将其转化成与锈蚀率η线性相关的量化指标I[75].如此一来,只要钢筋处于纵向磁化状态,磁化强度$\boldsymbol{M}$差异的不利影响就会被极大消除.事实上,由于轧制、受力和地磁场的磁化作用,钢筋的这种纵向磁化状态广泛存在[5,22,28-29,31,35-36,44,48,50,52-53,56,75-78].因此,目前采用式(3)所示的量化方法,提出了钢筋局部或整体锈蚀情形下,与锈蚀率η线性相关的各种漏磁量化指标[30,35-36,48,50,53,56,75-76].不过,量化指标I在理论上要求的理想纵向均匀磁化实际上很难完全满足.钢筋的磁化强度$\boldsymbol{M}$除了主要的纵向分量M_x,亦有随机分布的

次要分量(切向分量M_y和法向分量M_z),这也是图3(a)中线性关系出现离散性的根源.

由图3(b)可见:文献[76]提出的另一个量化指标I_c与锈蚀率η之间的线性关系离散程度较高,不能直接用于评估钢筋的锈蚀率η;借助于贝叶斯理论可将其转换为基于实测I_c数值的锈蚀率η分级评估结果.



(a) Quantification of MFL



(b) Classification of rebar corrosion degree

图3　漏磁量化处理和钢筋锈蚀率分级评估结果

Fig. 3　Quantification of MFL and classification of rebar corrosion degree [75-76]

这种基于概率的方法可以合理考虑钢筋在非理想纵向磁化状态下引起的评估误差,相似研究汇总于表1.由表1可见,基于各漏磁量化指标可以获得较好的锈蚀率η评估精度,而且采用多个指标进行综合评估精度更高;在钢筋锈蚀率η很低或较高时准确率可达90%以上[30,35,50,76].

上述结果表明,利用漏磁技术对钢筋锈蚀率η进行探测和评估具有很好的应用潜力.但目前,不同研究中构造的量化指标并不统一,如何选定一个最优指标或者指标组合值需要进一步研究.此外,针对图3(b)中钢筋锈蚀率η的概率分布进一步拓展,以用于锈蚀梁的时变可靠性分析.由于锈蚀梁锈胀裂缝宽度与锈蚀率η有显著的离散线性关系,先基于机器学习模型,根据实测裂缝宽度估计锈蚀率η的概率分布;再采用蒙特卡洛有限元分析,即可获得如图4所示的锈蚀梁抗弯承载力的概率分布[18].按照类似思路,基于漏磁探测数据可实现对锈蚀钢筋混凝土结构的受力性能进行概率评价和时变可靠性分析.根据表1中的信息,使用多个漏磁量化指标或结合锈斑面积、裂缝宽度等信息,能够获得准确度更高的评估结果.

4　钢筋锈蚀特征漏磁测评的影响因素

由于现有各种量化指标通常使用无外加荷载裸钢筋、外包混凝土试件和矩形截面梁的漏磁数据,无法全面考虑钢筋应力、疲劳损伤、箍筋/相邻纵筋漏磁干扰、锈蚀产物和混凝土的影响.对于铁磁性材料,理论上已证明应力变化会使其磁化强度M出现非线性变化[80-82].图5为应力水平、疲劳、箍筋/相邻纵筋、锈蚀产物和混凝土对锈蚀钢筋漏磁的影响.

由图5(a)可见,钢材从加载状态到极限状态过

表1 基于漏磁量化指标的锈蚀率概率量化评估

Table 1 Probabilistic assessment of corrosion degree η based on MFL quantification indices

Resource	Index	Assessment method	Assessment accuracy
Ref. [35]	Quantitative K_G	Bayesian model	56.8%-97.4%
Ref. [76]	Quantitative K_c	Bayesian model	65.0%-95.7%
Ref. [30]	Non-quantitative β, quantitative γ	Bayesian model SVM	57.1%-100.0% of single index, 85.7%-100.0% of double indices, and the classification accuracy of SVM exceeds 90.0%
Ref. [50]	Non-quantitative β, quantitative γ	Bayesian model	56.6%-100.0% of single index, 83.3%-100.0% of double indices
Ref. [48]	Non-quantitative M_1, M_3, M_4; quantitative M_2	SVM	The classification accuracy of SVM is 77.7%
Ref. [36]	Quantitative K, rusty spot area S	Bayesian model	70.0% of only K, 82.5% of K&S
Ref. [79]	Peak, peak-valley spacing	BP neural network	9.5%

Note: SVM is support vector machine.

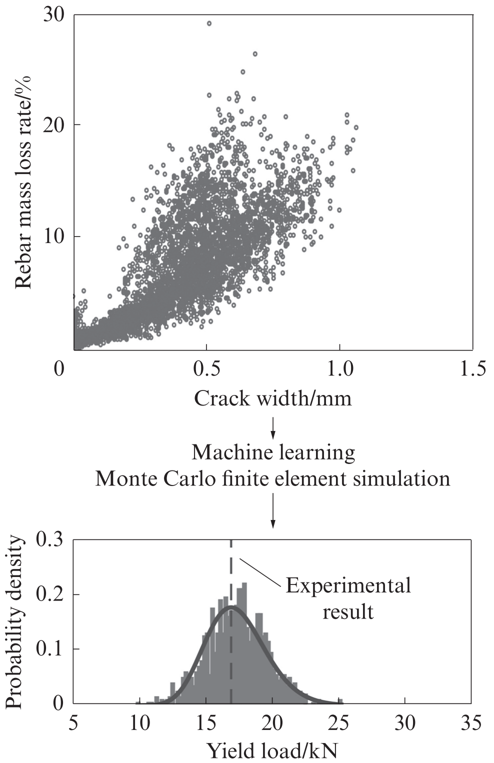


图4 基于锈胀裂缝宽度的混凝土锈蚀梁抗弯承载力概率分布估计

Fig. 4 Probability distribution estimation of flexural capacity of corrooded RC beam based on corrosion crack width [18]

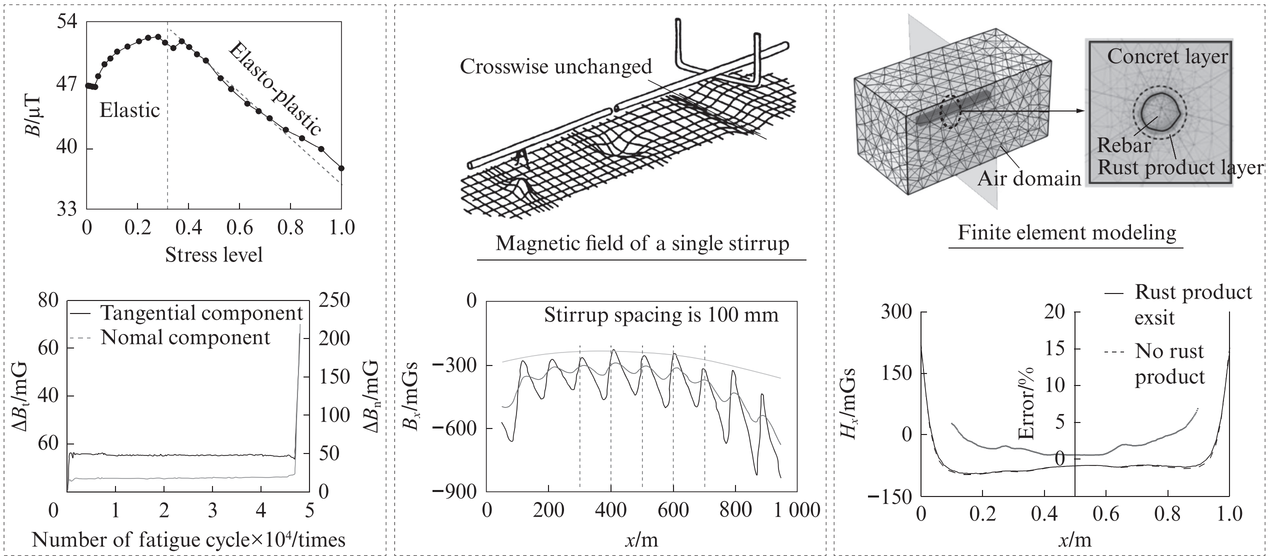
程中，其漏磁数值B随着应力水平的增加呈现先非线性增加后近似线性下降[83-84]的变化趋势．钢材处在弹性阶段时B的非线性增长源自钢材磁化强度$\boldsymbol{M}$的非线性增加[80-82]，而弹塑性阶段时B的线性下降是由于占据主导的塑性损伤产生了类似于锈蚀的漏磁[85-86]．当锈蚀与持续荷载作用同时存在时，钢筋混凝土梁的漏磁变幅ΔB随着锈蚀率η的增加而线性增大[63]，与图2(a)、(b)中无荷载线性结果一致．该研究中钢筋的最大锈蚀率η为0.063，由锈蚀所导致的应力增幅不超过6.7%，表明较小范围的应力变化对锈蚀的漏磁影响有限．在弹性应力循环作用下，钢筋的漏磁变幅ΔB与应力幅之间有良好的线性关系[77,87-89]，与图5(a)中静力加载的弹性阶段相似．

由图5(a)还可见：随着疲劳次数的增加直至疲劳破坏，漏磁变幅ΔB的切向分量ΔB_t和法向分量ΔB_n与疲劳荷载次数的线性关系扩展为“三段式”[90-92]；第2段的水平线性段是由于该阶段拉伸应力使钢筋的磁畴纵向重取向（磁化强度$\boldsymbol{M}$）趋于稳定；随着疲劳次数的增加，塑性微观损伤累积诱发的钢筋宏观缺陷使得ΔB_t和ΔB_n在第3段线性陡升．整体上看，疲劳加载过程中漏磁的绝对值与静力加载一样均先升后降，这种相似性的本质在于静力和疲劳都使钢筋经历了“磁畴纵向重取向—微观损伤累积—宏观缺陷漏磁”这一物理过程．此外，尽管钢筋的疲劳漏磁研究案例已有不少，但较为完善的疲劳与锈蚀的耦合研究尚未见报道．

由图5(b)可见：箍筋同纵筋锈蚀一样也会引起漏磁场的变化[21]；纵筋锈蚀缺陷诱发的漏磁场变在横向上存在局域性，而在箍筋上基本保持不变；箍筋引起的纵向漏磁分量B_x曲线出现周期性波动[28]，且此现象亦常见于其他研究[23,32,38-39,49,67,70,78]．该周期性波动可通过算法进行滤除或将箍筋漏磁部分从整体场强中进行解耦处理．当然，这是箍筋的存在对锈蚀

纵筋漏磁的影响，此外还需要考虑箍筋的锈蚀对锈蚀纵筋漏磁的干扰．通常，箍筋出现锈蚀会先于纵筋且其锈蚀形态不易预测，此时锈蚀箍筋的漏磁不再是图5(b)中易于处理的分布形式．已有研究指出，混凝土梁中箍筋的锈蚀会延缓纵筋漏磁的发生，但不会显著改变锈蚀全过程中纵筋漏磁量值的增长趋势[5]．然而，如何准确解耦分离纵筋和箍筋的锈蚀漏磁尚无报道．此外，锈蚀纵筋的漏磁场还会受到相邻纵筋的影响，目前也无针对性的完善研究．总而言之，未来箍筋和相邻钢筋的漏磁干扰还有待深入分析．

外部探测到的钢筋漏磁场强度与相邻纵筋μ_0密切相关[5,20]．在工程实践中探测漏磁时，磁传感器与锈蚀钢筋之间的锈蚀产物和混凝土均会影响探测结果．一般而言，这种影响可以通过锈蚀产物和混凝土的相对磁导率μ_{rp}和μ_{rc}来考虑．磁性γ-Fe_2O_3和Fe_3O_4使锈蚀产物的相对磁导率μ_{rp}通常要比真空(或空气)磁导率μ_0(1.0)大[57]，文献[56]中测得地磁环境下μ_{rp}在1.45～1.87之间，接近1.0，而钢筋的相对磁导率μ_{rs}取值通常为100～10 000[24,58,63,65-66,69]．因此，设置$\mu_{rs}=200$，$\mu_{rc}=1.00$和$\mu_{rp}=1.87$，根据文献[56]中的静磁有限元仿真流程简略分析锈蚀产物对漏磁的影响，结果如图5(c)所示．钢筋的纵向磁化强度采用一个0.1 T的剩余磁通密度纵向分量来模拟．钢筋的外部设置有环向厚度约为5 mm的锈蚀产物层，该层的相对磁导率设置为1.00和1.87，以分别模拟有/无锈蚀产物．结果显示，有无锈蚀产物的漏磁场纵向分量H_x曲线几乎重叠，两者之间的误差基本不超过5%，与文献[57]中建议的3%漏磁强度修正比例接近．已经证明，基于该静磁有限元仿真流程得到的钢筋自发漏磁场强、分布与实际情况具有很好的一致性[56]．因此，根据图5(c)中的数值解可以初步判断锈蚀产物的影响是微小的，当然更准确的分析后续尚须深化．



(a) Stress/fatigue-induced magnetic flux density (ΔB) changes　(b) Periodic magnetic field variations caused by stirrups　(c) Effect of rust products on magnetic flux leakage field

图5　应力、疲劳、箍筋/相邻纵筋、锈蚀产物和混凝土对锈蚀钢筋漏磁的影响

Fig. 5　Effects of stress, fatigue, stirrups/adjacent steel bars, rust products, and concrete on MFL of corroded rebar[21,28,56-57,84]

5　建议的钢筋锈蚀特征漏磁探测评估流程

综上所述，一旦相关研究得以完善，即可根据图6所建议的流程进行混凝土结构钢筋锈蚀特征的漏磁探测与评估．首先，基于高精度磁探测设备获得的锈蚀钢筋混凝土结构近表面漏磁场数据，进行漏磁成像并应用计算机视觉自动识别锈蚀位置和宽度．同时，根据式(3)给出的量化理论定义并计算漏磁量化指标I. 在此基础上，进一步考虑应力和箍筋等因素的影响并予以修正，得到修正的量化指标I_m；随后，根据I_m及基于I的锈蚀率η标准概率密度函数，得到I_m所对应的锈蚀率η概率密度分布．此外，融合多指标或多技术信息还可获得精度更高的评估结果．如此，即可达成基于漏磁的混凝土结构钢筋锈蚀特征精细化定量评估的目标．

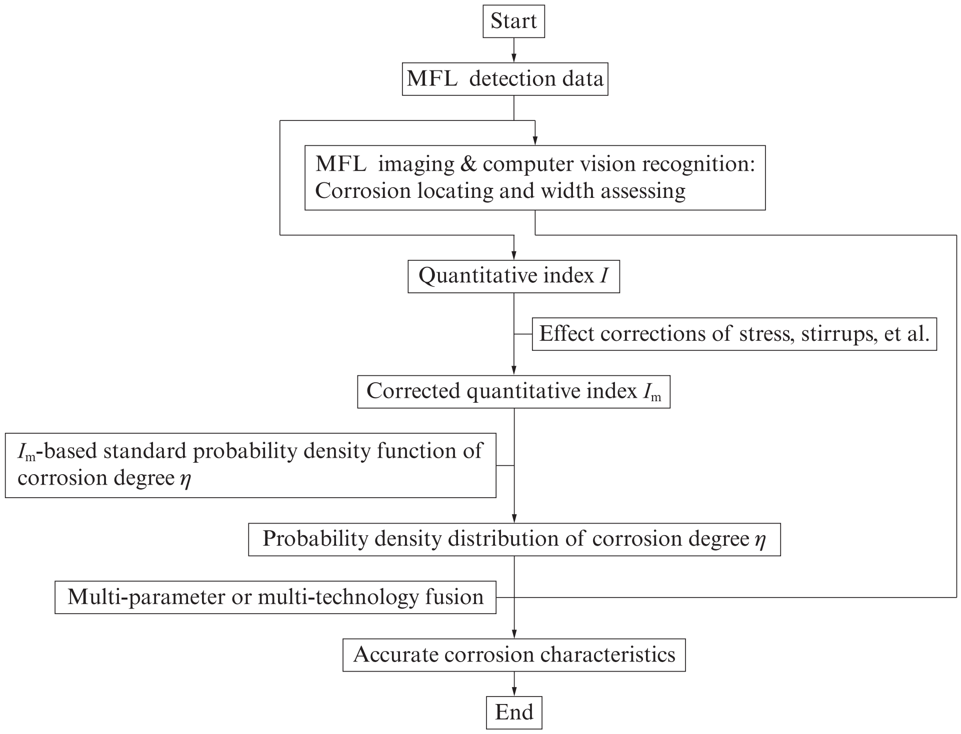


图6　建议的钢筋锈蚀特征漏磁探测评估流程

Fig. 6　Proposed process for MFL-based detection and assessment of rebar's corrosion characteristics

6　结论与展望

(1)应当考虑钢筋随机磁化分布引起的钢筋锈蚀率量化评估结果的随机性,发展基于概率的钢筋锈蚀率定量评估方法.

(2)明确应力、疲劳、锈蚀箍筋/相邻纵筋和锈蚀产物的影响.

(3)基于漏磁成像和计算机视觉能够自动识别锈蚀位置和锈蚀率.

(4)将多指标或多技术进行融合,以进一步提升钢筋锈蚀率评估精度.

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