

Contents

| | |
|--|-----------|
| <i>Contributor contact details</i> | <i>xi</i> |
| Part I Failure mechanisms | 1 |
| 1 Progress in failure criteria for polymer matrix composites: a view from the first World-Wide Failure Exercise (WWFE) | 3 |
| A. S. KADDOUR and M. J. HINTON, QinetiQ, UK | |
| 1.1 Introduction | 3 |
| 1.2 Aims of the first World-Wide Failure Exercise (WWFE) | 5 |
| 1.3 Setting up test problems | 7 |
| 1.4 Description of available models | 9 |
| 1.5 Design problems solved | 9 |
| 1.6 Gaps identified | 17 |
| 1.7 Current activities | 17 |
| 1.8 Conclusions | 22 |
| 1.9 Acknowledgements | 22 |
| 1.10 References | 22 |
| 2 Manufacturing defects as a cause of failure in polymer matrix composites | 26 |
| K. POTTER, University of Bristol, UK | |
| 2.1 Introduction and basic requirements | 26 |
| 2.2 Sources of variability and defects in composite mouldings | 27 |
| 2.3 Impact of residual stresses and geometrical distortions on performance | 29 |
| 2.4 Impact of voidage and delaminations on in-plane and out-of-plane properties | 32 |
| 2.5 Impact of misaligned, wavy and wrinkled reinforcements on in-plane and out-of-plane properties | 33 |

| | | |
|-----|---|-----|
| 2.6 | Approaches to minimize the impact of manufacturing defects | 46 |
| 2.7 | Future trends | 49 |
| 2.8 | References | 51 |
| 3 | Low- and medium-velocity impact as a cause of failure in polymer matrix composites R. OLSSON, Swerea SICOMP AB, Sweden | 53 |
| 3.1 | Introduction | 53 |
| 3.2 | Impact damage | 54 |
| 3.3 | Impact response | 57 |
| 3.4 | Strength and stability after impact | 66 |
| 3.5 | Computational models | 71 |
| 3.6 | Future trends | 73 |
| 3.7 | Sources of further information and advice | 74 |
| 3.8 | References | 75 |
| 4 | Structural integrity of polymer matrix composite panels in fire P. GU, University of California at San Diego, USA | 79 |
| 4.1 | Introduction | 79 |
| 4.2 | Temperature distribution | 81 |
| 4.3 | Material behavior at elevated temperature | 86 |
| 4.4 | Global buckling | 89 |
| 4.5 | Skin wrinkling of sandwich panels | 94 |
| 4.6 | Plastic micro-buckling | 98 |
| 4.7 | Other aspects of structural integrity in fire | 102 |
| 4.8 | References | 106 |
| 5 | Testing the toughness of polymer matrix composites M. J. LAFFAN, Imperial College London, UK | 110 |
| 5.1 | Introduction | 110 |
| 5.2 | Interlaminar fracture toughness testing | 111 |
| 5.3 | Translaminar fracture toughness testing | 117 |
| 5.4 | Ply-level fracture toughness testing | 119 |
| 5.5 | Conclusions | 126 |
| 5.6 | References | 126 |
| 6 | Testing the strength and stiffness of polymer matrix composites J. M. HODGKINSON, Imperial College London, UK | 129 |
| 6.1 | Introduction | 129 |
| 6.2 | Key issues | 130 |

| | | |
|--|--|------------|
| 6.3 | In-plane testing | 134 |
| 6.4 | Out-of-plane testing | 166 |
| 6.5 | Biaxial in-plane testing | 172 |
| 6.6 | Triaxial testing | 175 |
| 6.7 | Concluding comments | 176 |
| 6.8 | References | 177 |
| 7 | Fibre-dominated compressive failure in polymer matrix composites S. T. PINHO, R. GUTKIN, S. PIMENTA, N. V. DE CARVALHO and P. ROBINSON Imperial College London, UK | 183 |
| 7.1 | Introduction | 183 |
| 7.2 | The physics of fibre kinking in unidirectional plies | 184 |
| 7.3 | Compressive failure in two-dimensional woven composites | 203 |
| 7.4 | Compressive failure in recycled composites | 213 |
| 7.5 | Conclusions | 218 |
| 7.6 | Acknowledgement | 219 |
| 7.7 | References | 219 |
| Part II Failure mechanisms in specific applications | | 225 |
| 8 | Considerations of failure mechanisms in polymer matrix composites in the design of aerospace structures T. K. Tsoutsis, The Boeing Company, USA | 227 |
| 8.1 | Introduction | 227 |
| 8.2 | Design considerations | 229 |
| 8.3 | Structural considerations | 229 |
| 8.4 | Designing for damage in composites | 248 |
| 8.5 | Materials-based approaches | 248 |
| 8.6 | Structures-based approaches | 255 |
| 8.7 | Conclusions | 266 |
| 8.8 | References | 271 |
| 9 | Failure of polymer matrix composites in defence applications K. DRAGAN and A. LESKI, Air Force Institute of Technology, Poland | 279 |
| 9.1 | Introduction | 279 |
| 9.2 | Ballistic damage of composite structures | 280 |
| 9.3 | Implications for preventing failure | 285 |
| 9.4 | Trends in modeling composite failures in military applications | 293 |
| 9.5 | References | 298 |

| | | |
|-------|---|-----|
| 10 | Failure of polymer matrix composites in marine and off-shore applications P. DAVIES and D. CHOQUEUSE, IFREMER, France and H. DEVAUX, HDS, France | 300 |
| 10.1 | Introduction | 300 |
| 10.2 | Material types | 303 |
| 10.3 | Failure of composite materials for surface vessels | 306 |
| 10.4 | Failure of composite materials for underwater structures | 322 |
| 10.5 | Modelling failure | 333 |
| 10.6 | Future trends | 333 |
| 10.7 | References | 333 |
| 11 | Recycling issues in polymer matrix composites V. GOODSHIP, University of Warwick, UK | 337 |
| 11.1 | Introduction | 337 |
| 11.2 | The problems of reuse in polymer composites | 340 |
| 11.3 | Plastic waste disposal into other materials | 341 |
| 11.4 | Mechanical recycling of polymeric matrix composites | 342 |
| 11.5 | Recovery techniques | 352 |
| 11.6 | Properties of recovered fibres | 358 |
| 11.7 | Future strategies for making polymer matrix composites more recyclable | 359 |
| 11.8 | Conclusions | 361 |
| 11.9 | Sources of further information and advice | 363 |
| 11.10 | References | 363 |
| 11.11 | Appendix: abbreviations | 367 |
| 12 | Failure of polymer matrix composites (PMCs) in automotive and transportation applications P. K. MALLICK, University of Michigan-Dearborn, USA | 368 |
| 12.1 | Introduction | 368 |
| 12.2 | Polymer matrix composites (PMCs) used in automotive and road transportation applications | 369 |
| 12.3 | Scope of the chapter | 369 |
| 12.4 | Common in-service conditions causing failure | 370 |
| 12.5 | Sheet molding compound (SMC) composites | 371 |
| 12.6 | Polymer matrix composites (PMCs) for crashworthy structures | 382 |
| 12.7 | Implications of preventing failure | 388 |
| 12.8 | Future trends | 389 |
| 12.9 | References | 390 |

| | | |
|--------------|--|-----|
| 13 | Environmental induced failure in fibre-reinforced plastics W. BROUGHTON, National Physical Laboratory, UK | 393 |
| 13.1 | Introduction | 393 |
| 13.2 | Chemical agents and degradation mechanisms | 395 |
| 13.3 | Environmental conditioning and testing | 414 |
| 13.4 | Modelling and predictive analysis | 425 |
| 13.5 | Optimising chemical resistance and prevention of failure | 430 |
| 13.6 | Conclusions and future trends | 431 |
| 13.7 | Sources of further information and advice | 433 |
| 13.8 | Acknowledgements | 433 |
| 13.9 | References | 434 |
| 13.10 | Appendix: standards | 437 |
| <i>Index</i> | | 441 |