# Chapter 6

# Conclusion

## 6.1 General Conclusions

The work presented in this thesis has shown several important aspects in dealing with SMA-composites. In general it was found that the field of SMA-composites is relatively young. There is a lot of potential in the use of SMA-composites, however an understanding of the behaviour of the composites under many different conditions is essential if they are to be used in civil or aerospace structures of any type.

This thesis has investigated aspects of the behaviour of SMA-composites and in particular has looked at the recovery stress behaviour. Several important aspects of SMA-composite behaviour have been shown. The impact damage behaviour of composites was also investigated, which is particularly important for applications in civil, aerospace or automotive structures. Applications of SMA-composites were also discussed in this thesis including crack patching. The major findings of this thesis work are summarised below:

Concerning the transformational characteristics of the SMA-composites:

- Little effect was observed on the transformational temperatures of the constrained wires. Transformational heats decreased substantially with increasing pre-strain.
- The transformational behaviour of constrained SMA wires has been found to

be related to self-accommodating and preferentially oriented martensite. The self-accommodating nature of the martensite was found to be unaffected by pre-straining, embedding and processing of the wires. However the constraining nature of the matrix does suppress the preferentially oriented martensitic transformation.

SMA wires of differing composition were tested and the following results were found:

- The hysteresis curve for the strain-temperature behaviour of the wires decreases with increasing load. The smaller the hysteresis the better for embedment into composites due to easier heating capabilities. The smallest hysteresis was found in an R-phase NiTi alloy (ths150r) and a NiTiCu alloy (mes150m).
- There is a linear relationship between the resistance and the strain of SMA wires, which would be useful in measuring changes to the wires, such as pre-strain or detecting damage.
- The maximum recovery stresses were the same for 3% and 6% pre-strains compared to 1% pre-strain, which was lower. This similarity is due to the wires at 3% and 6% continuing to transform above 140°C, whereas the transformation of the wires at 1% is complete.
- Stability tests of the wires found that there was a decrease in the recovery stress stability over time for some of the wires. The most stable wire alloys were found to be the NiTiCu (mes150m) alloy, the NiTi R-phase alloy (ths150r) and the superelastic NiTi alloy (ths150a).
- The most appropriate wire alloy for embedment into composites for recovery stress generation was found to be the NiTiCu (mes150m) alloy due to the small hysteresis loop and long term cyclic stability.

Concerning the thermomechanical properties of the SMA-composites:

- SMA-composites are capable of generating recovery stresses of up to 140 MPa are obtainable.

- By increasing the wire fraction it is possible for the strain to increase with respect to temperature. Varying the pre-strain of the wires showed no effect on the strain-temperature or the stress-strain behaviour.
- There was no observed change in the maximum recovery stress with differing pre-strain due to recovery stress generation continuing above 140°C.
- The temperature to which the composites are heated is an important factor in the generation of recovery stresses. It was found that when the SMA-composites were heated to higher temperatures the recovery stresses generated degrade over time, whereas at lower temperatures of around 110°C the recovery stresses remain stable during thermal cycling to that temperature, ensuring a good recovery stress transfer from the wires to the composite.

Concerning the impact damage characteristics of SMA-composites:

- It was determined that increasing the pre-strain of the superelastic SMA wires decreased the size of the projected damage area of the composite.
- The best position of the wires for embedment was between a 0° ply and any other ply. This prevents resin rich areas from forming around the wires, since the wires become incorporated along the matrix fibre direction.
- By increasing $V_f$ of wires in a composite decreases the amount of through damage occurring. The fibre breakage of the specimen decreases.
- It was also determined that there was an equivalent amount of damage occurring in impacted specimens when compared with embedded wires of other types, for eg. steel or martensitic NiTiCu or NiTi SMA wire. This result is a good indication that by embedding superelastic SMA wires into composites for applications does not degrade the material's impact damage behaviour in any way.
- For high energy impact (within the low velocity impact range) the SMA wires tended to prevent more of the damage induced. In particular the through damage was lower for superelastic wires than for other types of wires.

- the SMA-composites have good damping and energy absorption capabilities in comparison to the other wire types and it was also found that they have a reasonably low damage accumulation after impact.

Concerning SMA patches:

- The analytical calculations for the use of SMA patches to close cracks in existing structures show promising results. Closure stresses of up to 19 MPa were predicted.
- Numerical modelling was performed using FEM and showed promising reductions in stresses along the centre of an aluminium structure.
- In general it was shown that a simple linear elastic model for modelling the behaviour of SMA-composites is not always appropriate due to the complex thermomechanical and transformational behaviour of the SMAs.

## 6.2 Prospects for Future Work

Further work in the area of impact damage characterisation would be useful, particulary if a larger $V_f$ of wires were embedded into the specimens. By increasing $V_f$ the superelastic behaviour of the wires may be advantageous in preventing or reducing the damage during impact. Large amounts of SMA wires embedded into a composite might be useful in high velocity impact. By determining the effects of varying $V_f$ of wires in the SMA composite an optimal design for SMA-composites for use in structures can be determined, and from that, costs and effective uses of the composites can be determined.

One of the major problems encountered with the use of SMA-composites is the cost of production. An improved method to pre-strain and embed wires into composite materials needs to be developed . Perhaps incorporating pre-strained wires in the pre-preg stage or automating the process of winding the wires, because, as was seen in this investigation, by hand winding the wires it is not only time costly, but, depending on the type of wire used, incorrect pre-strains can be induced.

The promising reductions in stresses found by the FEM and analytical modelling within specimens due to an attached SMA patch would indicate that experiments involving attaching such a patch to a structure should be carried out. Of interest would be investigating the best way to bond a SMA patch to a structure, looking at the peel stresses at the edges of the patches and also experimenting on the increase in fatigue life of structures that have an attached patch.

The development of a detailed analytical model which incorporates the non-linear behaviour of the SMAs embedded into composites would be advantageous, particularly with the view to using it to determine different properties of the alloys and composites for different applications.

SMA-composites, in their infancy, have already shown a great deal of promise for use in civil structures, and it will not be long before they will be used in other areas such as aviation, high speed transport and automotive industries which require some sort of frequency control, improved damping behaviour or shape control within the structure.