International Journal of Scientific & Engineering Research, Volume 4, Issue 5, May 2013
ISSN 2229-5518

Experimental Analysis of Energy Dissipation in Small Diameter Nitinol wires

Chandra Mouli Vemury, Scott Renfrey

Abstract— This paper presents the methodology and findings of the experimental research carried out on small diameter Nitinol wires at Newcastle University. Among all compositions of Shape memory alloys (SMA), Nitinol is understood to be the most suited for use in the design of building and bridge structures subjected to earthquake loading conditions. The shape memory effect and superelasticity demonstrated by Nitinol lends to higher energy dissipation capability of this alloy and hence is suited for cyclic dynamic loading conditions. A series of static and cyclic dynamic tests were developed and conducted on Nitinol wires of 1mm, 0.5mm and 0.25mm diameters to assess their basic mechanical properties and energy dissipation capabilities. The results from these experiments agree with the trends suggested in the literature and show that smaller or thinner the diameter of a Nitinol wire greater is its energy dissipating capability.

Index Terms— Earthquakes, Energy Dissipation, Nitinol, Shape memory, Superelasticity, Re-centering, Hysterisis

◆

1 INTRODUCTION

NITINOL belongs to family of smart materials called Shape memory alloys (SMA), also known by the name Shape memory materials. As a result of the phase transformations experienced by SMA, they have the ability to undergo large deformations, yet, return to their undeformed shape. The recovery of the original shape occurs when the material is subjected to a change in temperature or removal of stress. The two features of SMA, such as Nitinol, that are relevant in their application in Seismic Resistant Design are Shape Memory Effect and Super Elasticity. Over the last few decades, SMA have been found to have numerous applications in fields such as medical surgery, aerospace and mechanical industries, electronics and communication engineering and sports industry. The ability of SMA to recover large deformations makes these materials ideal in the design of damper elements for earthquake resistant structures.

Some of the known compositions for shape memory alloys are Ni-Ti, Cu-Al-Ni, Au-Cd, Mn-Cu, Ni-Mn-Ga and Fe-based alloys. Among all of the SMA, Ni-Ti based alloys have wider applications due to the better ductility and strength and absence of grain-boundary fracture [1]. Binary Nickel-Titanium alloys are commonly addressed as Nitinol. A number of investigations have been carried out into the stress-stain and damping characteristics of SMA wires and bars [2], [3], [4], [5]. A prevalent finding from these studies is that the equivalent damping increases with a decrease in diameter of SMA bars or wires. It has been found that wires tend to have better energy dissipation characteristics than bars [2], however little research has been conducted to see if this trend continues as the diameter of an SMA wire decreases below 1mm.

A series of static and cyclic-dynamic tests were conducted on small diameter Nitinol wires at Newcastle University and this paper will present findings from the experiments carried out by the authors.

2 NITINOL AND ITS PROPERTIES

Nickel-Titanium based alloys, due to their superior mechanical properties, have wider applications in earthquake resistant design of building and bridge structures. These alloys are also known by various other names such as Nickel-Titanium, Titanium-Nickel, Tee-nee, Memorite, Tinel, and Flexon. These terms represent a family of alloys within which the properties of each is characterised by its exact compositional make-up, processing history and tertiary additions. Some of Nitinol's metallurgical and engineering properties have been listed in Table 1. The behaviour of Nitinol and other Nickel-Titanium alloys is sensitive to the percentage of titanium in the compound.

Table 1. Composition and Engineering Properties of Nitinol

	Nitinol Description
Nickel composition	55.0%-55.5% by wt
Titanium	44.5%-45.0% by wt
Microstructure	Very fine twinned martensite
Possible additions	O_2, Fe, Al, Cr, Co, V, Pt, Pd, Zr, Hf, Nb, Cu
Austenitic phase structure	B2 or CsCl
Martensitic phase structure	Monoclinic
Density	6.45 to 6.5 g/cm^3
M_s range	<-200^{o}C to +100^{o}C
Elastic Modulus for martensite	40 GPa
Elastic Modulus for austenite	75 GPa

2.1 Shape Memory Effect

SMA, when subjected to shear strain while below its Temperature Transformation Range (TTR), exhibit stress-strain behaviour characterised by a large hysteresis loop. At these temperatures, the microstructure of the material is fully martensitic and the hysteresis occurs due to the twinning deformation of Martensite. The strains achieved in this stage are not permanent. Upon heating the material to a temperature above TTR it reverts to the austenitic crystalline structure and the strains developed will be eliminated. This process of reverting to the original shape of the SMA is called Shape Memory Effect.

- *Mr. Chandra Mouli Vemury is a Teaching Fellow in Civil Engineering at School of Civil Engineering and Geosciences, Newcastle University, United Kingdom, PH-00441912227886. E-mail: chandra.vemury@ncl.ac.uk*
- *Mr. Scott Renfrey is a Graduate Structural Engineer at Gawn Associates, Cambridge, United Kingdom. E-mail: scott@gawnassociates.com*

2.2 Super Elasticity

When an SMA in its stable austenitic phase is subjected to elastic loading up to a threshold stress it undergoes a stress-induced transformation from Austenite to Martensite. The transformation takes place at a reduced value of modulus as found in the cases of plastic yielding. The increase in deformation is proportional to the increase in volume of Martensite within the material. The path of stress-strain curve follows a stress plateau during its journey to full martensitic transformation. Martensite is stable only in the presence of applied stress and so the unloading of the SMA causes reverse transformation. The SMA will return to its original undeformed shape upon full removal of the applied loads. This property of the SMA is very useful in the design of damping devices and is called Superelasticity.

3 EXPERIMENTAL STUDY

A number of properties possessed by SMA make them ideal materials in the design of energy dissipating devices such as damper elements. These dampers improve the ductility of the structure without comprising its strength during a seismic event. It has been found that Nitinol wires tend to have better energy dissipation characteristics than bars [2], however little research has been conducted to see if this trend continues as the diameter of an SMA wire decreases below 1mm. This investigation was aimed at providing an improved understanding of the behaviour of Nitinol wires of diameter less than 1mm when subjected to cyclic dynamic loading.

This study involved tests on Nitinol wires of three different diameters in order to characterise their basic mechanical properties and also their energy dissipation caracteristics. One of the sample-diameters used in this research is 1mm. This choice was made to allow for comparisons to be drawn with previous research [2], [3], [6], [7], [8] and to validate the results. The other two sample-diameters of 0.5mm and 0.25mm were chosen to offer a range below 1mm. Nitinol was chosen as its properties relevent to energy dissipation are all high relative to other commonly used SMA [9]. Also, Nitinol was used in tests conducted by Dolce & Cardone (2001), DesRoches et al. (2004) and Zhang & Zhu (2007) and offers a large scope for comparison. Nitinol is also mass produced due to its use in the medical and aerospace industries, making it easily available and economically viable for testing.

3.1 Static Testing Procedure

A static test procedure was developed to identify several important properties of the wires such as the plastic and ultimate failure loads, the stress-strain relationships resulting in the Young's modulus and the transition curve and key phase-transition points for each diameter wire. Due to the difficulties associated in measuring the strain of the samples until failure, an equation was generated to get the relationship between the extension measured by the Instron Unaxial Tensile Strength (UTS) machine and the strain experienced by the sample. In the static test, Nitinol wire samples were subjected to incremental tensile load using an Instron UTS machine. The load application continued until the wire samples reached plastic deformation. The load history, corresponding strain and axial displacement were recorded. This procedure was repeated on a total of 9 samples, three sets of equi-dimensional 3 wires. The point of plastic deformation identified on the stress-strain graph corresponds to the instance when the gradient changes from very small to high, it is where the sample leaves the martensitic phase and is known as the martensitic finish point (M_f). In order to verify this phase change point, an additional 'superelasticity' test was conducted where the wires were loaded until an extension of 10-20% below the suspected M_f extension level and then released, with the permanent elongation recorded. The wire was then loaded to 10-20% above the suspected M_f extension and then relaxed with the elongation again recorded.

3.2 Cyclic Dynamic Testing Procedure

The cyclic dynamic testing procedure used in this study simulates the forces experienced by a structure during an earthquake event. These tests establish the load-unload characteristics of the wires and from this the energy dissipation can be evaluated. A 5kN S-Type transducer load cell was attached to a GDS Large Diameter Cyclic Triaxial Testing System (GDS LDCTTS). Samples of 1mm, 0.5mm and 0.25mm diameters were cyclically loaded and unloaded at ± 10mm amplitude for 100 cycles. Two samples of each diameter size of the wire were tested at 0.5Hz and the third sample for each diameter size of the wire was to be tested at 1Hz and 2Hz. These frequencies (0.5Hz, 1Hz and 2Hz) are consistent with the frequencies of known earthquake events.

3.3 Static Test Results

As shown in Fig.1. the ultimate failure strains for the 0.25, 0.5 and 1mm wires were 10.7%, 11.2% and 9.3% and the ultimate failure stresses were 1556.42MPa, 1342.71MPa and 1012.78MPa respectively. Research by DesRoches, et al (2004) suggests that Nitinol wires could have ultimate tensile strengths in the range of 895-1900 MPa. Similarly, the findings of Janke et al. (2005) states 700-2000MPa as the range for ultimate tensile strength of Nitinol. All of the samples tested fell within this range, suggesting that the results comply with the findings of previous research.

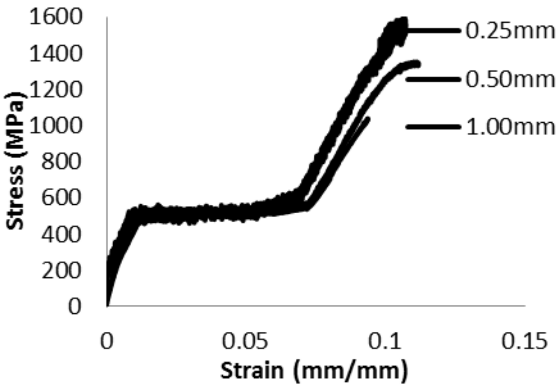

Fig. 1. Stress vs Strain Relationship under Static Test

The results for the ultimate tensile strength show that the thinnest wire could take more stress before ultimate failure (Table. 1). There appears to be a negative correlation between the thickness of the wires and the amount of stress required to reach ultimate failure, meaning a thicker wire reaches that stage under less stress. A study conducted by Norwich and Fasching (2004) into the fatigue effects of Nitinol wires produced the ultimate tensile stress values of 1680 MPa for 0.25mm wire and 1620 MPa for 0.5mm wire.

Table. 1. Phase transition points for 0.25mm dia Nitinol wire

Phase transition points	**Stress (MPa)**	**Strain (mm/mm)**
Test Start	87.59	0.00
Martensitic Start (M_s)	492.32	0.0085
Martensitic Finish (M_f)	590.11	0.068
Elastic Limit	1491.23	0.101
Failure Point	1556.42	0.107
E_1 (GPa)	47.6	
E_2 (GPa)	1.6	
E_3 (GPa)	27.3	
E_4 (GPa)	10.9	
E_3/E_1 (≤ 0.5)	0.57	
E_2/E_1 (≤ 0.1)	0.03	

These results also show that the thinner wire withstood higher stress. The variations in the ultimate tensile stresses could be due to variations in alloy compositions, Norwich and Fasching (2004) used a slightly different composition of Nitinol wire (Ti 55.9 Ni 44.1) compared to the one used in this study (Ti 55.8 Ni 44.2). Also, some sample failures occurred near the top of the sample as opposed to the middle of the span, this suggests additional shear stresses were induced by the holding mechanism and therefore the ultimate tensile strength is likely to be lower than it should be in this study.

Table. 2. Phase transition points for 0.50mm dia Nitinol wire

Phase transition points	**Stress (MPa)**	**Strain (mm/mm)**
Test Start	49.70	0.00
Martensitic Start (M_s)	520.54	0.010
Martensitic Finish (M_f)	550.32	0.072
Elastic Limit	1242.23	0.099
Failure Point	1342.71	0.112
E_1 (GPa)	52.0	
E_2 (GPa)	0.5	
E_3 (GPa)	25.6	
E_4 (GPa)	7.7	
E_3/E_1 (≤ 0.5)	0.49	
E_2/E_1 (≤ 0.1)	0.01	

The trend of the thinner wire achieving higher stress values before ultimate failure continues to be true when also looking at the elastic limit failure, where the average elastic limit stress values were 1491.23MPa, 1242.23MPa and 1012.78MPa for the 0.25, 0.5 and 1mm wires respectively. The 0.5mm wire took 22.7% more stress than the 1mm wire and the 0.25mm wire took 20% more stress than the 0.5mm wire before deformations became plastic. The strain values at the elastic limit point also increase as the wires get smaller, with an average elastic limit strain of 10.1%, 9.9% and 9.3% being recorder for the 0.25, 0.5 and 1mm wires respectively. Dolce and Cardone (2001) suggested that the Young's modulus for the austenitic section (E_1) should be between 30-70 GPa, this is the case for all the different diameter wires tested. However, no relationship or trend can be identified between the different diameter wires; it is believed that this is due to the curvature in the stress-strain relationship in the early austenitic phase. This curvature is indeed caused by the slack in the loading application system. Although attempts were made to remove this slack by applying a pre-tensioning force of 12N it appears this was not sufficient.

Table. 3. Phase transition points for 1.0mm dia Nitinol wire

Phase transition points	**Stress (MPa)**	**Strain (mm/mm)**
Test Start	17.96	0.00
Martensitic Start (M_s)	489.11	0.012
Martensitic Finish (M_f)	556.21	0.072
Elastic Limit	1012.78	0.093
Failure Point	1012.78	0.093
E_1 (GPa)	39.3	
E_2 (GPa)	1.1	
E_3 (GPa)	21.7	
E_4 (GPa)	N/A**	
E_3/E_1 (≤ 0.5)	0.55	
E_2/E_1 (≤ 0.1)	0.03	

The martensitic Young's modulus for the wires was found to be 27.3, 25.6 and 21.7 GPa for the 0.25, 0.5 and 1mm wires respectively. These values are consistent with the results obtained by Dolce & Cardone (2001) and the value suggested by Janke et al. (2005). The martensitic Young's modulus also appears to decrease as the diameter of the wire increases. This must mean that a thinner wire exhibits less strain as a load is applied during the martensitic phase. Under seismic loading conditions, a higher Young's modulus cycle will enclose more area and hence dissipate more energy. Therefore the initial static test suggests that the smaller diameter wires should dissipate more energy.

3.4 Cyclic Dynamic Test Results

The cyclic stress-strain curves for the wires tested generally fit the schematic stress-strain cycle for a superelastic SMA [2], [3], [4]. All of the graphs show that high strains can be achieved, nearly 12% for the 0.25mm wires, however when unloaded there are no "*residual deformations*" demonstrated by the fact all lines return to their start point dissipating energy in the process [4]. This superelastic property means that a SMA passive damper could help re-centre a structure bringing it quickly back to its original position after displacements caused by a seismic event [9]. The inverse transformations follow a similar shape to the forward transformation however the amount they are 'off-set' coupled with the distances between the transformation start and finish points affects the area contained within the hysteresis loop which is the amount of energy dissipated by the wire.

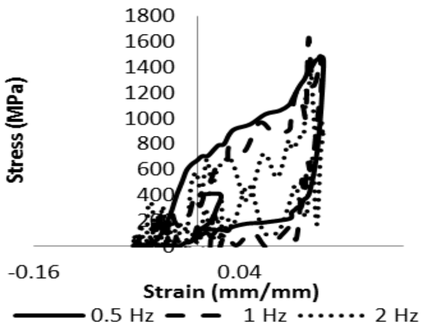

Fig. 2. Stress vs Strain Relationship under Cyclic Test for 0.25mm Nitinol wire

The σ_{Fs} is highest for the 0.25mm wire at around 600MPa, it decreases as the wires get thicker with the value at 270MPa and 100MPa for the 0.5mm and 1mm wires respectively. Similarly the σ_{Ff} is much higher for the 0.25mm wire at 1100MPa compared to around 500MPa for the larger diameter wires. The difference between the ε_{Fs} and ε_{Ff} is also much greater for the 0.25mm wire at 0.11mm/mm compared to 0.61mm/mm for the 0.5mm samples and 0.077mm/mm for the 1mm samples. The distance between the inverse and forward transformation (load and unload lines) is the greatest for the 0.25mm wire and appears to get smaller as diameter increases. This suggests that the 0.25mm stress-strain cycle encompasses the largest area and hence dissipates the greatest energy.

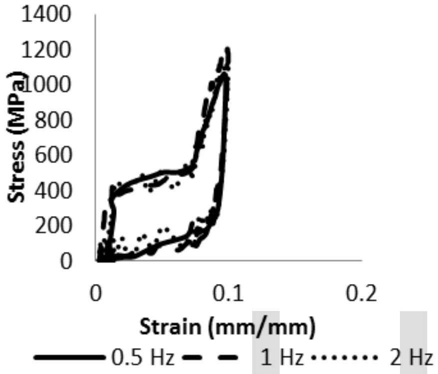

Fig. 3. Stress vs Strain Relationship under Cyclic Test for 0.50mm Nitinol wire

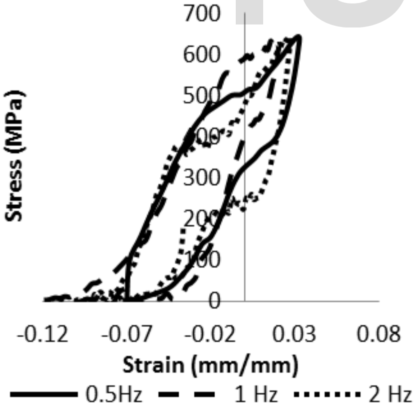

Fig. 4. Stress vs Strain Relationship under Cyclic Test for 1.00mm Nitinol wire

3.5 Energy Dissipation

The energy dissipated by the Nitinol wires during cyclic loading was calculated by simplifying the forward and inverse transformation lines into a polynomial expression. It was decided that a fourth order (x^4) polynomial gave sufficient detail. The raw values for energy dissipated in ascending order of diameter are 99.87MPa, 57.9MPa and 22.56MPa. These values must be scaled for each test and are therefore divided by the strain energy in the system multiplied by 4∏, giving Equivalent Viscous Damping values of 3.69%, 0.54% and 0.39% in ascending diameter. This clearly shows that the smaller the diameter the more energy dissipation and damping occurs.

Repeat cyclic test conducted by Dolce and Cardone (2001) on Nitinol wire samples "*with a diameter between 1-2mm found the equivalent damping to be of the order of 5-7%*". This is of a similar order to the values achieved in this study. Similarly, DesRoches, et al (2004) found the equivalent damping of a 1.8mm wire to be 6.88% for a 6% strain cycle which again is of a similar order to the values achieved by this study. This study's results may be lower due to the use of Differing percentage strain cycles, strains derived from extensions, experiments conducted at different frequencies and the simplification of hysteresis loops for area calculations in this study.

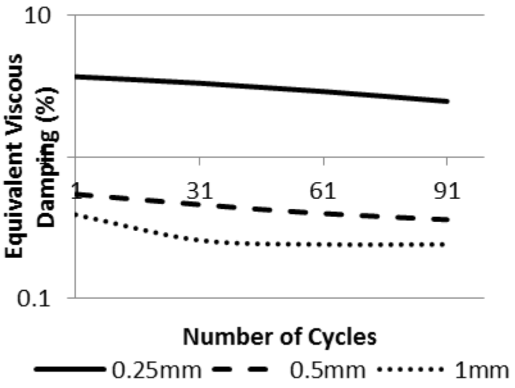

Fig. 5. Equivalent viscous damping on a log scale

Fig. 5 shows that as the number of cycles increased from 1 to 91 the material's ability to dissipate energy worsens, this could be important when designing dampers for seismic regions out of SMA as the amount of damping would reduce with each cycle. If the damper was designed with the energy dissipation values of the wire for the first cycle, after several cycles the damper could fail as the damping capabilities could decrease significantly.

4 CONCLUSIONS

Nitinol wires are found to have high energy dissipating capabilities. This characteristic of the shape memory alloy qualifies it to be an ideal material seismic resistant design of building and bridge structures. The authors have identified a gap in the body of research available on Nitinol wires. A series of static and cyclic dynamic testing procedures were developed and implemented on Nitinol samples of three different diameter-sizes. The execution of the two separate testing regimes has allowed a number of comparisons to be made across the samples studied and with the literature available in the public domain. Firstly, there appears to be a relationship between the amount of energy dissipated and the diameter of the wire under loading. The thinnest wire dissipated the most energy and this remains true when it is converted into a damping value relative to the strain energy within the system. The trends identified correlate with previous research [2], [4], [10], however the values obtained for equivalent viscous damping appear slightly lower than literature suggests due to likely errors and limitations within the methodology used. It is suggested that the higher damping capabilities of thinner wires mean that bundles of smaller Nitinol wires would generate more desirable damping results if used in a hyteretic passive damper.

All the wires tested experienced a decrease in their damping capabilities as the number of cycles increased. The largest increase was experienced by the 0.25mm wire which fell from 3.69% to 2.47%, over a 33% decrease in energy dissipation. The 1mm wire appeared to stabilise after a number of cycles as expected however the 0.25 and 0.5mm did not it is therefore expected that they would after more than 100 cycles. If Nitinol wires were to be used in the design of seismic dampers, this decrease in damping capabilities must be anticipated and accounted for perhaps through large safety factors or taking the damping characteristics of the metal once it has stabilised.

The austenitic Young's modulus of the wires all lay between the expected range of 30-70GPa and the martensitic Young's modulus generally fit the rule that it should be half the austenitic Young's modulus [3], [4]. A trend was identified that the thinner the wire the greater the martensitic Young's modulus, which fits with the theory that thinner wires provide greater damping. The superelastic nature of Nitinol wires of various diameters were confirmed through the cyclic test where all inverse transformations resulted in no "*risidual deformations*". If used in a seismic damper this superelastic quality would provide the structure with "*re-centering"* capabilities, meaning the building would be "*brought back to its original position*" by the SMA damper [3], [4], [9]. The authors, however, recognise that there is need for extended research on smaller diameter Nitinol wires subjected to varying conditions of temperature, heat treatment and higher frequencies of loads.

ACKNOWLEDGMENT

The authors wish to thank Dr. Sean Wilkinson, Dr. Mohamed Rouainia, Mr. Joe Hinchliffe and Dr. Gaetano Elia for their guidance and contribution to this experimental research. This work was made possible by the financial support extended by the School of Civil Engineering and Geosciences, Newcastle University.

REFERENCES

[1] K. Otsuka, and T. Kakeshita, "Science and Technology of Shape-Memory Alloys: New Developments," *MRS Bulletin*, vol. 27, no. 2, pp. 91-97, Feb. 2002.

[2] R. DesRoches, J. McCormick, and M. Delemont, "Cyclic Properties of Superelastic Shape Memory Alloy Wires and Bars" *ASCE Journal of Structural Engineering,* vol.130, no. 1, pp. 38-45, Jan. 2004.

[3] M. Dolce, D. Cardone, and R. Marnetto, "Implementation and testing of passive control devices based on shape memory alloys" *Earthquake Engineering Structural Dynamics*, vol. 29, no. 7, pp.945-968, Jul. 2000.

[4] M.Dolce, and D. Cardone, " Mechanical Behaviour of Shape Memory Alloys for Seismic Applications" *International Journal of Mechanical Sciences*, vol. 43, no.11, pp.2657-77, Nov. 2001.

[5] E.J. Grasser, and F.A. Cozzarelli, "Shape-memory alloys as new materials for aseismic isolation" *Journal for Engineering Mechanics*, vol. 117, no. 11, pp. 2590-2608, Nov. 1991.

[6] Y. Zhang, and S. Zhu, "A Shape Memory Alloy-Based Reusable Hysteric Damper for Seismic Hazard Mitigation" *Journal of Smart Materials and Structures,* vol. 16, no. 1, pp. 1603-1613, Aug. 2007.

[7] S. Zhu, and Y. Zhang, "Seismic analysis of concentrically braced frame systems with Self-Centering Friction Damping Braces" *Journal of Structural Engineering*, vol. 134, no. 1, pp. 121-131, Jan. 2008.

[8] S. Sweeney, and J. Hayes, "Shape memory alloy dampers for seismic rehabilitation of existing buildings" *Proceedings of the 27th Joint Meeting on Wind and Seismic Effects, U.S.-Japan Cooperative Program in Natural Resources, Tsukuba, Japan,* pp. 317-332, 1995.

[9] L. Janke, C. Czaderski, M. Motavalli, and J. Ruth, "Applications of Shape Memory Alloys in Civil Engineering Structures: Overview, Limits and New Ideas" *Journal of Materials and Structures,* vol. 38, no. 5, pp. 578-592, Jun. 2005

[10] D. W. Norwich, and A. Fasching, "A Study of the Effect of Diameter on the Fatigue Properties of NITI Wire" *Journal of Material Engineering and Performance,* vol. 18, pp. 558-562, Aug. 2009.