Review of Design of Hybrid Aluminium/ Composite Drive Shaft for Automobile

Mandar Deo[1] , Piyush Chavan[2], Varun Chippa[3], Saisha Dalvi[4], Nikhil Chavan[5]
[1, 2, 3, 4, 5] Department of Mechanical Engineering
[1, 2, 3, 4, 5] Marathwada Mitra Mandal's College Of Engineering, Karvenagar, Pune - 411052

Abstract- *In current market, drive shaft is the most important component to any power transmission application; automotive drive Shaft is one of this. A drive shaft, also known as a propeller shaft or Cardan shaft, it is a mechanical part that transmits the torque generated by a vehicle's engine into usable motive force to propel the vehicle. This topic deals with the study of replacement of conventional two-piece steel drive shafts with one-piece automotive hybrid aluminium/composite drive shaft & was developed with a new manufacturing method, in which a carbon fibre epoxy composite layer was co-cured on the inner surface of an aluminium tube rather than wrapping on the outer surface to prevent the composite layer from being damaged by external impact and absorption of moisture. The two-piece steel drive shaft consists of three universal joints, a center supporting bearing and a bracket, which increases the total weight of an automotive vehicle and decreases fuel efficiency. However, in this paper an attempt is made to evaluate the suitability of composite material for the purpose of automotive drive shaft application.*

Keywords- Drive shaft, composite material, Aluminium / composite drive shaft design. Press fitted Joints, Static Torque.

I. INTRODUCTION

An automotive drive shaft transmits power from the engine to the differential gear of a rear wheel drive vehicle. The torque capability of the drive shaft for passenger cars should be larger than 3500 Nm and the fundamental bending natural frequency should be higher than 9200 rpm to avoid whirling vibration. Since the fundamental bending natural frequency of a one-piece drive shafts made of steel or aluminium is normally lower than 5700 rpm when the length of the drive shaft is around 1.5 m, the steel drive shaft is usually manufactured in two pieces to increase the fundamental bending natural frequency because the bending natural frequency of a shaft is inversely proportional to the square of beam length and proportional to the square root of specific modulus. The two-piece steel drive shaft consists of three universal joints, a center supporting bearing and a bracket, which increases the total weight of an automotive vehicle and decreases fuel efficiency. Since carbon fibre epoxy composite materials have more than four times specific stiffness ($E= \rho$) of steel or aluminium materials, it is possible to manufacture composite drive shafts in one-piece without whirling vibration over 9200 rpm.

The composite drive shaft has many benefits such as reduced weight and less noise and vibration. However, because of the high material cost of carbon fibre epoxy composite materials, rather cheap aluminium materials may be used partly with composite materials such as in a hybrid type of aluminium/composite drive shaft, in which the aluminium has a role to transmit the required torque, while the carbon fibre epoxy composite increases the bending natural frequency above 9200 rpm.

II. THEORY

A) Composite Material

A material composed of 2 or more constituents is called composite material. Composites consist of two or more materials or material phases that are combined to produce a material that has superior properties to those of its individual constituents. The constituents are combined at a macroscopic level and or not soluble in each other. The main difference between composite and an alloy are constituent materials which are insoluble in each other and the individual constituents retain those properties in the case of composites, whereas in alloys, constituent materials are soluble in each other and forms a new material which has different properties from their constituents. Classification of Composites

- Polymer matrix composites
- Metal matrix composites
- Ceramic Matrix

B) Advantages Of Composite Drive Shaft

1. They have high specific modulus and strength.
2. Reduced weight.
3. Due to the weight reduction, fuel consumption will be reduced.
4. They have high damping capacity hence they produce less vibration and noise.
5. They have good corrosion resistance.
6. Greater torque capacity than steel or aluminium shaft.

7. Longer fatigue life than steel or aluminium shaft.
8. Lower rotating weight transmits more of available power

C) Limitations Of Composites

The limitations of composites are:

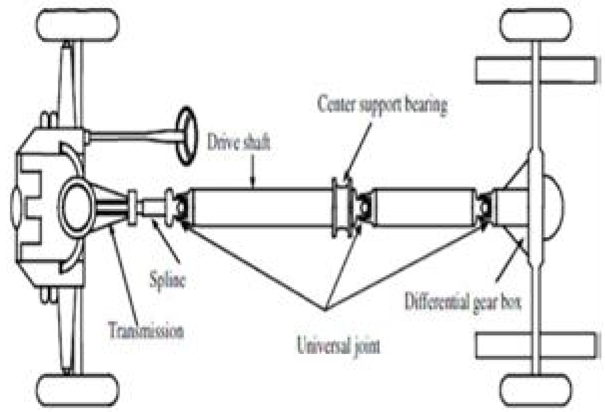
Mechanical characterization of a composite structure is more complex than that of a metallic structure, the design of fibre reinforced structure is difficult compared to a metallic structure, mainly due to the difference in properties in directions, the fabrication cost of composites is high, rework and repairing are difficult, they do not necessarily give higher performance in all properties used for material selection.

D) Demerits of A Conventional Drive Shaft

They have less specific modulus and strength and have increased weight. Conventional steel drive shafts are usually manufactured in two pieces to increase the fundamental bending natural frequency because the bending natural frequency of a shaft is inversely proportional to the square of beam length and proportional to the square root of specific modulus. Therefore the steel drive shaft is made in two sections connected by a support structure, bearings and U-joints and hence over all weight of assembly will be more. Its corrosion resistance is less as compared with composite materials and steel drive shafts have less damping capacity.

E) Merits Of Hybrid Aluminium/Composite Drive Shaft

They have high specific modulus and strength and reduced weight. A one-piece composite shaft can be manufactured so as to satisfy the vibration requirements. This eliminates all the assembly, connecting the two piece steel shafts and thus minimizes the overall weight, vibrations and the total cost. Due to the weight reduction, fuel consumption will be reduced. They have high damping capacity hence they produce less vibration and noise. They have good corrosion resistance and greater torque capacity than steel shaft. Longer fatigue life than steel shaft. Lower rotating weight transmits more of available power.



Conventional Two-Piece Steel Drive Shaft[2]

III. PROBLEM DESCRIPTION

Generally the bending natural frequency of a shaft is inversely proportional to the square of the unsupported (beam) length and directly proportional to the square root of specific modulus. Therefore lesser the length of a shaft between supports, the overall weight of a single shaft will become less for a given material. Hence the conventional steel drive shafts (propeller shafts) of a commercial vehicle are usually made in two pieces, which leads to increased fundamental bending natural frequency. The drive shaft of a commercial vehicle made in two sections connected by a support structure, bearings and U-joints.

However this construction increases the weight of the assembly due to the additional centre support bearings and other mountings. Together these parts need to be maintained and serviced regularly which adds for the maintenance cost. The problem can however be solved by replacing the conventional two piece steel drive shaft with single composite drive shaft which can full-fill the functionality of an automotive drive shaft without any weight.

IV. DESIGN REQUIRMENT OF COMPOSITE DRIVE SHAFT

The objective for the optimum design of the composite drive shaft is the minimization of weight, so the objective function of the problem is given as

$$m = \rho AL \quad \text{.....} \quad (1)$$

However this objective function is constrained by the functional requirements of the shaft, which are

Static load carrying capability of the shaft : $\sigma_d \geq \sigma_{max}$

Bucking torque capacity of the shaft:

$T_{cr} \geq T_{max}$

Fundamental natural frequency in bending: $N_{crt} N_{max}$

And the design parameters of the shaft for an automobile are given in table 3.1. The objective function is optimized by varying the stacking sequence, number of layers and lay thickness for different composite material using particle swarm optimization technique to meet the design requirement.

Table 3.1 Design requirements of the shaft for an automobile [3]

Parameters	Valules
Outer diameter d_o (mm)	90
Length L(mm)	1250
Torque transmitted T(N-mm)	3500×10^3
Speed of Transmission N(rpm)	6500

V. ANALYTICAL RELATION TO CALCULATE THE CRITICAL LOAD OF COMPOSITE SHAFT

In the design of composite shafts before applying the finite element technique, a closed form solution is useful. In order to have an order-of-magnitude solution for a design, a simple equation is needed to calculate the torsional buckling load of long thin-wall shafts. There are various existing equations for this purpose in the literature. These equations are empirical, obtained based on experimental studies. The equation considered to find the buckling load is taken from reference [2].

$$T_{cr} = (2\pi r^2 t)*(0.272)*(E_x E_y^3)^{0.25}* (t/r)^{1\cdots}(2)$$

Where, 'Ex' and 'E_y ' are the Young's modulus of the composite shafts in axial and hoop direction 'r' and 't' are the mean radius and thickness of the composite drive shaft.

VI. FINITE ELEMENT ANALYSIS

In this work, finite element model of steel and various composite drive shafts is developed for the optimized results obtained from particle swarm optimization [4] using ANSYS V 10 solver. The geometry and material properties of steel and composite drive shaft considered are shown in table 5.1 and 5.2 respectively. Since the geometry of the model is simple, an assumption of linear isotropic material for steel and linear orthotropic material for composites is made.

The element considered for modelling steel and composite shaft are shell 93 and shell 99 respectively. Each element is having 8 nodes and each node is having 6 degrees of freedom. The finite element model with load and boundary condition is shown in Figure 4.1.

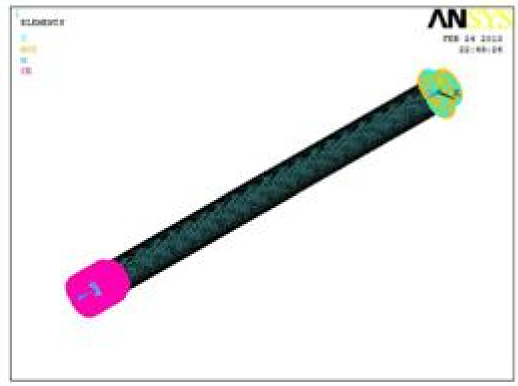


Fig 4.1 Load and boundary conditions applied on the shaft[4]

Table 4.1 Geometrical properties of various shafts [4]

Parameter	Steel (SM45 C)	Kevlar49/ Epoxy	HM-Carbon/ Epoxy
Optimum Layers	-	16	17
Thickness t(mm)	3.32	6.8	2.04
Optimum Stacking sequence	-	[-46/73/39/50/-43/20/-24/-43/$\overline{38}$]s	[-23/-51/68/-56/-72/47/-20/46/$\overline{22}$]s
T (Nm)	3500	3500	3500

Table 4.2 Material properties of various shafts[4]

Parameter \ Material	Kevlar49/ Epoxy	HM-Carbon/ Epoxy
	21.0	37.49
Ey (GPa)	15.49	56.83
Gxy (GPa)	15.97	33.88
V12	0.35	0.39
Density (Kg/m3)	1500	1600

Static Analysis

For static analysis the shaft is fixed at one end and the other end a torque of 3.5×10^6 N-mm is applied on rigid element (rbe3) created at center of shaft at a distance of 1150mm.

The Von Mises and shear stress distribution of various shafts are shown in figure 5.2 to 5.7.

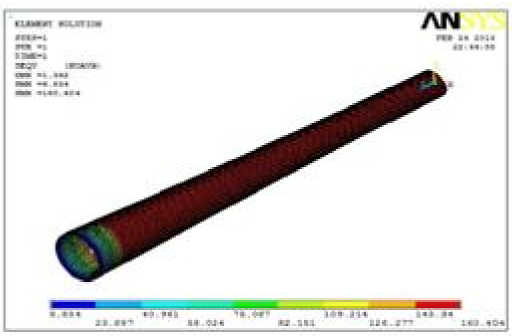


Fig 4.2 Von Mises Stress Distribution of Steel Drive Shaft[4]

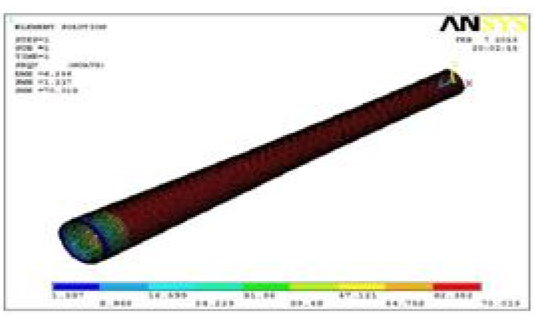


Fig 4.3 Von Mises Stress Distribution of Kevlar49/Epoxy Drive Shaft[4]

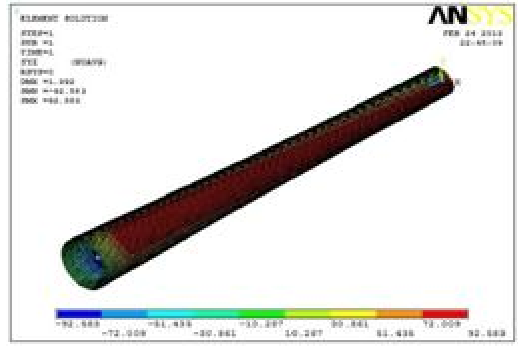


Fig 4.4 Von Mises Stress Distribution HM Carbon/Epoxy Drive Shaft[4]

Fig 4.5 Shear Stress Distribution of Kevlar49/Epoxy Drive Shaft [4]

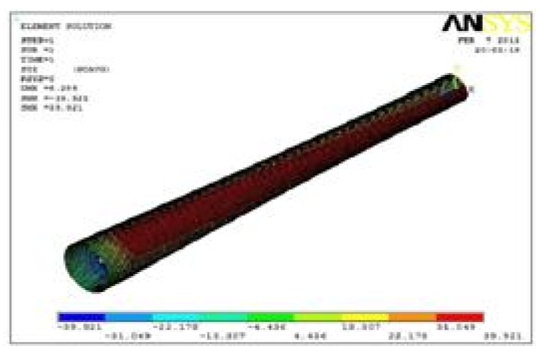


Fig 4.6 Shear Stress distribution of Steel Drive Shaft[4]

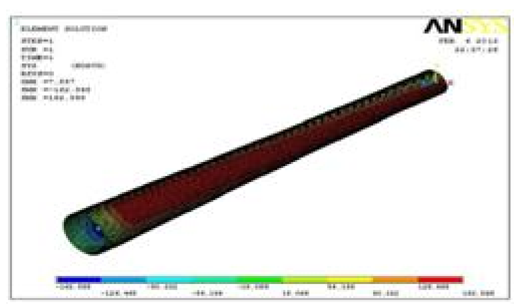


Fig 4.7 First Bending Mode of Steel Drive Shaft[4]

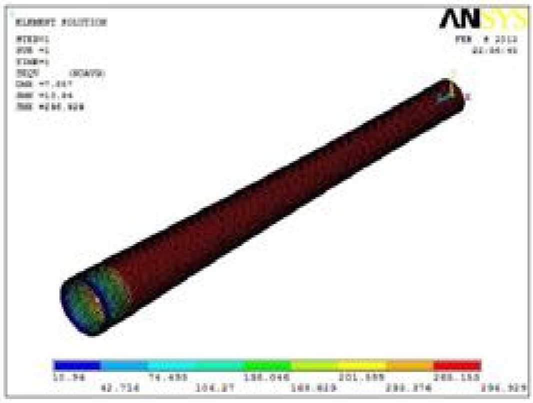


Fig 4.8 Shear Stress Distribution Of HM-Carbon/Epoxy Drive Shaft[4]

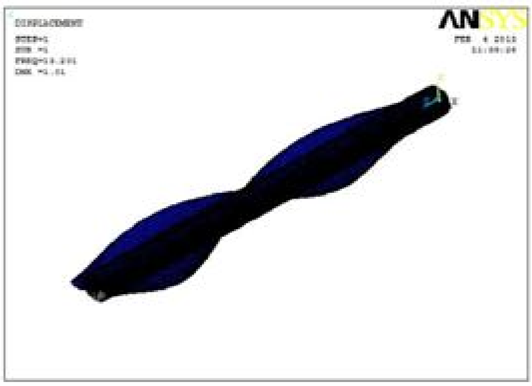


Fig 4.9 First Bending Mode Kevlar 49/Epoxy Drive Shaft[4]

Modal Analysis

Modal analysis deals with un-damped free vibration of a structure. It does not involve any computation of response due to any loading, but yields the natural frequencies and corresponding mode shapes. For Eigen value analysis the boundary conditions are assumed as pinned-pinned condition. The first mode shapes obtained for Steel, Kevlar49/ Epoxy and High Modulus Carbon/Epoxy materials using ANSYS V 10 are shown in figures5.8 to 5.10 respectively. The frequencies of first modes are multiplied by 60 to obtain critical speeds of drive shaft.

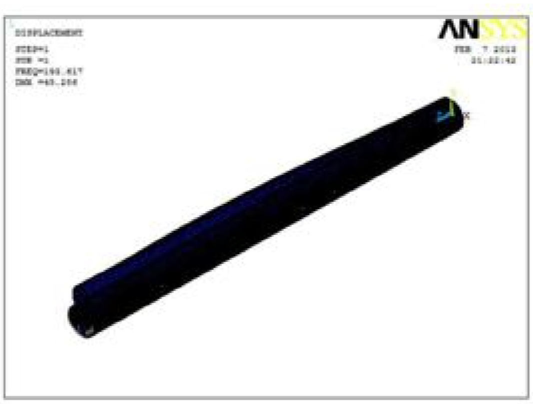


Fig 4.10 First bending mode Kevlar HM-carbon epoxy shaft[4]

Fig 4.11 First Torsional Buckling Mode of Steel[4]

Buckling Analysis

Torsional buckling analysis is performed to get the critical torsional buckling load. The buckling frequency and its corresponding mode shapes obtained for Steel, Kevlar49/ Epoxy and High Modulus Carbon/Epoxy using ANSYS V 10 are shown in figures from 5.11 to 5.13. The buckling strength is calculated by multiplying the critical speed with buckling load factor.

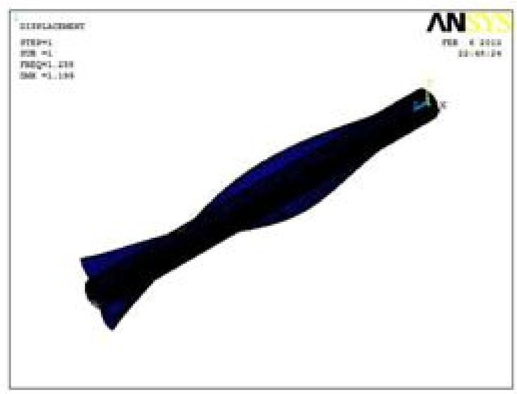


Fig 4.12 First Torsional Buckling Mode of HM-Carbon/Epoxy Drive Shaft[4\]

V. RESULT AND DISCUSSION

Static Analysis of Steel and Composite Drive Shafts

The analysis is carried out with one end fixed and a torque of 3.5 $\times 10^{6}$ N-mm at other end. The shear and vonmises stresses obtained from solver are compared with theoretical results and are tabulated in table 6.1 and 6.2 respectively. The shear strength is used to describe the strength of a shaft where the ductile material fails in shear. FEA solver results, shows that torque carrying capacity is more in Kevlar49/Epoxy composite shaft than conventional steel driveshaft. The steel and HM Carbon/Epoxy have lesser shear strength.

Table 5.1 Comparison of Shear strength[4]

Material / Stresses (Mpa)	Steel	Kevlar49/ Epoxy	HM-Carbon /Epoxy
Theoretical shear stress	175	461	396
ANSYS V10 Shear stress	92.58	39.92	162.59

Table 5.2 Comparison of Von Mises Stress[4]

Material / Stress	Steel	Kevlar49/ Epoxy	HM Carbon/ Epoxy
Theoretical Vonmises Stress	370	1400	1600
ANSYS Vonmises Stress	160.40	70.01	296.92

Modal Analysis of Steel and Composite Drive Shafts

The analysis is used to determine the natural frequencies and corresponding mode shapes to find the critical speed of the shaft. Using solver, first natural frequency and its mode shape is extracted as the first few natural frequencies are more critical and dominated to failure. The critical speed obtained from FE solvers for steel and, Kevlar49/Epoxy and HM Carbon/Epoxy composite material and calculated from PSO. It is observed that Kevlar49/Epoxy shafts have minimum amount of critical speed compared to the other material shafts. The critical speed depends upon the shaft dimensions, materials and loads. In design optimization, the shaft dimensions and load are constant but stacking sequence is varied. As the critical speed depends upon stiffness and density, the material having high stiffness value will have maximum critical speed. Finally it is evident from the table5.3 that composite materials have more torque carrying capability. This clearly establishes the fact that torque capability of any material is reflected through critical speed values. Buckling analysis predicts the theoretical buckling strength of an ideal elastic structure. It is the mathematical instability leading to a failure mode. Buckling loads are critical loads where the solvers for steel and Kevlar49/Epoxy and HM Carbon/Epoxy composite material are tabulated in table 5.3. The HM Carbon/Epoxy material have load factor around and have very low critical buckling torque. It is observed that the buckling strength of the composite shafts is less compared to steel shaft of the same geometry because these properties depend on the stiffness and cross section of the material. It also depends upon the length to radius ratio (L/R), radius to thickness ratio (R/t) and unsupported length. Therefore, the composite shaft Kevlar49/Epoxy has higher critical buckling torque

Table 5.3 Buckling Analysis Results[4]

Material	Steel	Kevlar49/ Epoxy	HM-Carbon /Epoxy
Load factor	13.201	8.901	1.258
Torque obtained from ANSYS (Nm)	46203	31153	4403

5.5 Validation

Using Eq. (2) and data from table 3.1, 5.1 and 5.2 the theoretical buckling torque is calculated for kevlar49/Epoxy and HM Carbon/Epoxy.

For Kevlar49/Epoxy,

$T_{cr}=(2\pi*41.6^2*6.8)*(0.272)*\{21.04*10^3*(15.49*10^3)^3\}^{0.25}*(6.8/41.6)^{1.5}$

$=22226$ Nm

For HM-Carbon/ Epoxy,

$T_{cr}=(2\pi*43.98^2*2.04)*(0.272)*\{37.49*10^3*(56.83*10^3)^3\}^{0.25}*(2.04/43.98)^{1.5}$

$= 3450$ Nm

The FE and theoretical results are compared and tabulated in table 6.5. It is observed both results have good agreement with each other.

Table 5.4 Comparison of buckling torque[4]

Material		Kevlar49/ Epoxy	HM-Carbon /Epoxy
Theoretical Buckling Torque (Nm)	45193	22226	3450
Torque obtained from ANSYS (Nm)	46203	31153	4403

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CONCLUSION

When a long monolithic hollow composite driveshaft is subjected to torsional load, an instability occurs which is more critical in the design of composite drive shaft. The prominent failure mode of composite drive shaft is shear buckling rather than material failure. In this work an attempt is made to check the suitability of one piece composite drive shaft with various composite material combinations to fulfill the functional requirements. Firstly, a finite element model of composite drive shaft made of Steel SMC45, Kevlar49/Epoxy and HM Carbon Composite is developed and analyzed for static, modal & buckling analysis using ANSYS 10.

Results clearly indicate that,

1. The optimized composite drive shafts designed using particle swarm optimization technique is safe under the peak torque loading of 3500Nm and rotational speed of 6500rpm.
2. The single piece steel drive shafts fail in shear.
3. Kevlar/Epoxy and HM Carbon/ Epoxy shafts are good in shear strength and bending natural frequency and are excellent from vibration point of view.
4. Kevlar/Epoxy has good buckling strength capability as compared with other composites.

The obtained Finite element analysis results are compared with analytical values and observed that the single piece composite drive shaft is better suitable for driveline applications. Thus the designed single piece composite drive shafts can be employed in the automobiles to result for considerable weight savings, thereby increasing the fuel efficiency. However, high material processing cost together with its limited availability is a major limitation of the composite materials which need to be addressed, to make the employment of composite driveshaft in the automobile economical.

REFERENCES

[1] K.V.N. Parvathi,CH. Prabhakara Rao Research Paper- "Structural Design of Composite Drive Shaft for Rear Wheel Drive Engine"; (E-ISSN2249–8974)

[2] Madhu K.S., Darshan B.H., ManjunathK; Research Paper- Buckling Analysis Of Composite Drive Shaft For Automotive Applications. ; (ISSN: 2320 1932);Volume No.1A, Issue No.2, Page No: 63 -70

[3] Bhushan K. Suryawanshi, Prajitsen G.Damle Research Paper- Review of Design of Hybrid Aluminium/ Composite Drive Shaft for Automobile; International Journal of Innovative Technology and Exploring Engineering (IJITEE) ISSN: 2278-3075, Volume-2, Issue-4, March 2013

[4] Madhu K.S.[1], Darshan B.H.[2], Manjunath K.[3] Research Paper-" Bucking Analysis Of Composite Drive Shaft for Automotive Application."*(ISSN: 2320 1932) Vol.No.1A,Issue No.2,Page.No.:63-70,Jan-Jul 2013.