CHAPTER 1

Introduction

The ever increasing demand for power to support and sustain the requirements of world population of 7.0 billion (in 2011) is dictating the optimum use of energy and materials. Fracture of engineering materials is a problem that society has faced for a long. Major airline crashes, failures of high pressure pipe lines, bursting of liquid and gas storage tankers etc are just a few examples of catastrophic failures. An economic study (Duga et al., 1983) estimated the cost of fracture in the United States in 1978 at around $ 120 billion, about 4% of gross national product. This data is sufficient to indicate that how detrimental these catastrophic failures are to the economy. Moreover, this study also provided an estimate of the annual cost that could be reduced if further research is directed towards understanding and predicting the failure behaviour of materials. Thus, it is a little surprise that substantial efforts are being made worldwide in this direction with a broad objective of developing more robust structural integrity assessment methods so that the safety and integrity of the load bearing components/structures can be reliably assured.

Nuclear power generation is considered to be one of the clean and sustainable sources of energy. At present around 20% of electricity in US and 74% in France is generated through nuclear energy. India has an ambitious plan to extend its power generation capacity through nuclear energy to 20,000 MWe by 2020. Safe and reliable operation of nuclear power plants is an essential requirement to satisfy the public concern of safety besides the obvious economic aspects.
Welding is one of the most widely used fabrication process in the nuclear power plants. It is used to join permanently two, usually metallic, components by the application of heat and/or pressure. The range of pressure and temperature used may vary a lot depending up on the particular welding technique but heating and cooling are integral parts of most welding process. The particular combination of these variables results in a joint that is unique in terms of material variation, potential flaws, and residual stresses. Material variations occur across a weld joint because each region of weld is subjected to a different thermal history, with temperatures rising, in some cases, above those required for phase transformation and grain growth. In a typical multi-pass weld in steels, for instance, several regions may develop in the heat affected zone, each with its own microstructure and mechanical and fracture properties. In cases where filler metals are used the weld metal may have significantly different chemical composition than the base metal and, hence, may possess different mechanical properties. Such material variations can affect significantly both the fracture toughness and the crack driving force in a weld joint. The welding process also largely controls the potential for weld defects which may develop during fabrication. The common defects developed during welding include lack of penetration, lack of fusion, which are planar defects, and slag inclusions and porosity, which are volumetric defects. Cracks may also develop during welding. Planar defects and cracks have direct consequences on the structural integrity of weldment, while volumetric defects may eventually pose problems due to fatigue crack initiation during service.

Conventional defect assessment procedures that are being used at present were essentially developed for cracks lying in a homogeneous material. In view of the variations in the tensile and fracture properties of base and weld material, the integrity assessment of
strength mismatch welds is not straightforward. Here mismatch means that the weld and base material differ in yield strength and in hardening behaviour. In addition the difference in elastic modulus and Poisson’s ratio also occurs in certain cases. However, for engineering materials that are used in bridges, offshore equipments, piping and pressure vessels, the difference in the elastic properties is usually small (Hao et al., 1997). Thus, these structures need specific attention on the mismatch problem under elastic-plastic condition. Although finite element analysis may be used to carry out integrity assessment of strength mismatch weld on case by case basis, however, for engineering applications a simplified fracture assessment procedure is invariably preferred. In this study accurate analytical solutions of the limit load, plastic $\eta$-factor and crack tip stress fields of plane strain fracture specimens having weld centre crack are presented. Proposed analytical solutions were validated by detailed elastic-plastic finite element analyses. It is expected that the detailed analytical and numerical studies performed in this work would provide a comprehensive understanding of the effects of weld strength mismatch on the limit load, plastic $\eta$-factor and crack tip stress fields of plane strain fracture specimens.

### 1.1 Fracture assessment procedures for welds

Most of the commonly used fracture assessment procedures developed for welds require an accurate evaluation of the limit load. For materials having high fracture toughness the net-section collapse occurs prior to crack growth initiation and, thus, the limit load provides a good estimate of the load bearing capacity of the component. However, for materials having moderate or low fracture toughness the criterion of net section yielding is not
adequate and detailed fracture mechanics calculations are required. Apart from accurate evaluation of crack driving force like J-integral, the material fracture toughness is also required for such integrity assessment calculations. In general, plastic $\eta$-factor is used for the experimental evaluation of fracture toughness. Fracture testing standards like ASTM E-1820 provides the plastic $\eta$-factor for standard homogeneous fracture specimens. Effects of weld strength mismatch on the plastic $\eta$-factor have not been incorporated till date.

Conventionally, fracture toughness tests are performed on small size standard fracture specimens. Detailed analytical and experimental studies conducted in past two decades have revealed that the crack-tip stresses play an important role in the fracture process. Since the state of stress near the crack tip in a standard fracture specimen is very different from that of the component/structure under investigation, significant variations in the fracture toughness of standard fracture specimen and the actual component have been observed.

Thus, extensive studies are required on welds as besides specimen geometry and loading conditions the strength mismatch ratio $M$ (defined as ratio of yield strength of weld to yield strength of base material) and weld slenderness ratio $\psi$ (defined as ratio of uncracked ligament to half weld thickness) are the additional variables affecting the fracture assessment parameters.

1.2 Identification of issues for investigation

A detailed literature survey (presented in Chapter 2) revealed that in the past two decades several detailed numerical (FE) and experimental studies have been performed on weld
centre crack. Although the effect of strength mismatch ratio $M$ and weld slenderness ratio $\psi$ on fracture assessment parameters has been numerically as well as experimentally examined, however, the detailed insight of the mechanics of deformation in a strength mismatch weld is still lacking. The detailed structure of global plastic fields that occurs in commonly used fracture specimens, having weld centre crack, under fully plastic condition has not been worked out. Aspects related to the state of stress at the base-weld interface need a more thorough investigation. The general structure of crack tip stress field and particularly the angular variation of these local stresses need a detailed examination. The important concern of characterisation of crack tip stresses for weld centre crack under mode I loading needs to be studied. It remains to be established that the effect of specimen geometry, loading condition and weld strength mismatch can be suitably represented by appropriate crack tip constraint parameters. The present work is intended to address these issues.

1.3 Scope of work

In this work, detailed analytical and numerical studies were envisaged on weld centre crack under mode I loading. Both base and weld materials were modeled as elastic-perfectly plastic (non-hardening). It is well recognized that such idealised model does not adequately represent the real material behaviour, however, this material model was chosen for the present study because of three prime reasons; (i) an insight into the physics of deformation of solids can be obtained by this simplified material response. (ii) Limit load has been widely used as an important design parameter. It is worth to note that the assumption of
non-hardening plasticity is a necessary requirement for limit analysis. The effect of strain hardening is accounted indirectly by adjusting the reference stress, in general, as an average of yield and ultimate tensile strength. In addition, the experimental evaluation of fracture toughness requires a proportionality factor, often referred as the plastic $\eta$-factor. Analytical evaluation of plastic $\eta$-factor also invokes the assumption of non-hardening plasticity. (iii) The results of crack tip stresses obtained from this idealized material model may still be applicable for materials having low and even moderate strain-hardening. For homogeneous standard fracture mechanics specimens it has been demonstrated by O’ Dowd and Shih (1991) that the constraint parameter Q is a weak function of material strain hardening behaviour.

Thus, in the present investigation, both base and weld materials were modeled as elastic-perfectly plastic. The two materials were assumed to have same elastic modulus and Poisson’s ratio but mismatch in their yield strength. All the investigations in this work were carried out on deeply cracked fracture specimens under plane-strain condition. A schematic of geometries investigated in present work is shown in Fig.1. Crack was postulated at the centre of weld. Numerical studies were performed within the framework of continuum scale plasticity ($J_2$ flow theory) and effects of micro-structural heterogeneity and presence of residual stresses were not accounted.

1.4 Objectives of the thesis

The objectives of the present thesis are as follows
• To develop a robust analytical method for plane-strain problems that can account for weld strength mismatch effects.

• To develop accurate analytical solutions of the limit load for commonly used fracture mechanics specimens having weld centre cracks.

• To study the effects of strength mismatch ratio \( M \) and weld slenderness ratio \( \psi \) on the state of stress near the crack tip in high as well as in low constraint geometries namely pure bending SE(PB) specimen, compact tension C(T) specimen, and middle tension M(T) specimen having weld centre crack.

• To propose analytical solutions of the plastic \( \eta \)-factor (used for experimental evaluation of fracture toughness) for fracture specimens having weld centre cracks.

• To propose the general structure of crack tip stress field in an elastic-perfectly plastic material under mode I loading. To study the suitability of 4-sector stress field proposed by Zhu and Chao (2001) for the problem of weld centre crack. To examine whether the combined effects of specimen geometry, loading conditions and weld strength mismatch can be suitably represented by a general structure of crack tip stress field.

• To develop constraint parameters that can be used to characterize the crack tip stresses in an elastic-perfectly plastic material under mode I loading. To study the suitability of the proposed constraint parameters for a wide range of crack tip constraint. To identify whether the proposed constraint parameters are adequate to represent the effects of specimen geometry, loading conditions and weld strength mismatch on crack tip stresses.
• To perform detailed 2-D elastic-plastic full field finite element analysis on both high constraint and low constraint geometries having weld centre crack under mode I loading. To validate the structure of proposed general elastic plastic crack tip stress field with the results of crack tip stresses obtained from FE analysis.

1.5 Organisation of the report

The work carried out in this thesis is organised in nine chapters. The structure of the remaining part of this report is as follows:

Chapter 2 of this thesis describes a detailed literature survey that is conducted to understand the studies performed by various researchers on fracture aspects of strength mismatch welds under monotonic loading. Both analytical and experimental studies are covered. For the sake of completeness a brief description of the studies performed on homogeneous fracture specimens is also provided.

In chapter 3 of this thesis, general aspects related to the assumption of rigid plastic material model, virtual work principle, and limit theorems of classical plasticity are introduced. The concept of proposed Modified Upper Bound (MUB) theorem and its analytical formulation are presented. It is demonstrated that the method (MUB) is actually a new form of already existing extremum/work principle.

In chapter 4, the equivalence of proposed MUB theorem with the classical Slip line Field (SLF) analysis, for a rigid-plastic body in plane strain, is discussed. It is demonstrated that minimization of this new form of general work principle automatically leads to global equilibrium equations, as obtained from SLF analysis. Both cracked and
uncracked configurations are analysed to establish this equivalence in general. As a novel application a complete analytical formulation for yield locus for the entire range of tensile and bending load, for a single edge notched specimen, is presented.

In chapter 5, weld strength mismatch effects on the limit load and crack tip constraint is examined. The detailed structure of global plastic fields for pure bending SE(PB) specimen, and compact tension C(T) specimen having weld centre crack, under fully plastic condition, is presented. Aspects related to the state of stress at the base-weld interface are discussed. Effect of strength mismatch ratio M and weld slenderness ratio $\psi$ is systematically examined. Using the proposed MUB theorem accurate analytical solutions of the limit load, and crack tip constraint parameter $h$ are obtained. It is shown that a family of five fields proposed in this work is adequate to cover all practical cases of weld mismatch. Proposed analytical solutions are confirmed with detailed FE results.

In chapter 6, weld strength mismatch effects on low constraint geometries is analysed. As a representative of such a case, a middle tension M(T) specimen is analysed. A discontinuous stress solution is proposed to analyse M(T) specimen having a weld centre crack. Discontinuity is incorporated in the proposed solution by assuming an unknown value of normal stress at the base-weld interface. MUB theorem along with global equilibrium equations is utilised to obtain this unknown normal stress and hence the whole plastic field. The results obtained are found to be in excellent agreement with the known FE solutions available in literature. In addition to limit load, detailed evaluation of crack tip constraint is performed.

In chapter 7, the effects of weld strength mismatch on fracture toughness testing are discussed. Analytical solutions of plastic $\eta$-factor for pure bending specimen, compact
tension specimen and middle tension specimen having weld centre cracks are proposed and compared with finite element results.

In chapter 8, the important concern of characterisation of crack tip stresses in an elastic-perfectly plastic material under mode-I loading is discussed. A novel 5-sector asymptotic crack tip stress field is developed for a stationary crack under plane strain condition. Detailed 2-D elastic plastic finite element analyses are performed to examine validity of the proposed 5-sector stress field. A new constraint-indexing parameter $T_{CS-2}$ is proposed which along with hydrostatic stress ahead of crack tip is capable of representing the entire elastic plastic crack tip stress fields over all angles around a crack tip. Finally, it is demonstrated that the proposed constraint parameters are adequate to represent the crack tip constraint arising due to combined effect of specimen geometry, loading conditions, and weld strength mismatch effects.

In chapter 9, a brief summary of the entire work and salient conclusions drawn from the present investigation are presented. In addition, further possible extension of the present study that may be carried out in future is also discussed.
Fig. 1.1: Geometries investigated in present work (a) Pure bending SE(PB) specimen, (b) Middle tension M(T) specimen and (c) Compact tension C(T) specimen having a weld centre crack