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Numerical and experimental study on cutting access opening in ship structure

Bo ZHOU^{1,2}, Xiaoshuang HAN², Wei GUO², Zhongchi LIU², Soon-Keat TAN^{2,3}

¹School of Naval Architecture and Ocean Engineering, Dalian University of Technology, Dalian, China

²Maritime Research Centre, School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

³Nanyang Environment and Water Research Institute, Nanyang Technological University, Singapore

Abstract

Creating an access opening in ship structure through thermal cutting is an important process in ship repair and reconstruction. The flame cutting process typically leads to a non-uniform temperature distribution, generates residual thermal stress and localized plastic deformation. As openings are needed at various locations of ship hulls, it is also necessary to consider the effects of structural constraints in the immediate end of the plate where it is either welded or fixed to the ship frame or bulkhead. These are challenging tasks. This paper presents a study based on thermal elastoplastic analysis. By using the finite element techniques, a steel plate model undergoing flame cutting process to create an opening was studied in details. The numerical model was validated with experimental data. The study identified several key parameters and they are: (a) structural boundary condition, (b) steel plate size, (c) opening location, and (d) opening shape.

Keywords: Flame cutting; Cutting opening; Numerical simulation; Residual stress; Shipbuilding.

1 Introduction

During ship reconstruction, it is often necessary to temporarily create openings on ship structure for ready access of equipment or workers. Cutting opening process is an extremely complex thermal process which involves the physical reactions of the hull material subject to the cutting flame. Because of high concentration of heat input, uneven cooling and often non-symmetry, there would always be inevitable residual stress and deformation after the cutting opening process. These stresses are known to significantly impact the fatigue and stability of welded structures. The quality of cutting is influenced by many factors, highly non-linear and very difficult to simulate accurately. Several thermal cutting techniques, including flame cutting, laser cutting, electron beam cutting, plasma jet cutting, etc., have been adopted in the shipbuilding industry. As the equipment is of relatively low cost and convenient to use, flame cutting is commonly used for cutting access opening in shipyard. However, compared to other steel cutting methods, flame cutting process produces the undesirable effect of combustion of metal, instead of melting or evaporation of the metal, see Powell et al. (1993).

Cutting process, especially Laser cutting, has been studied and most of the studies were conducted numerically as can be found in the literatures. A three-dimensional heat-transfer model based on the finite difference method was developed by Mazumder and Steen (1980). The method allows for the formation of the keyhole by considering the grid points within the keyhole as part of the conducting network but operating at high temperatures after evaporation. Kim et al. (1993) formulated a two-dimensional model using triangular finite elements for transient analysis of material removal by evaporation. Yu (1997) presented numerical studies of laser cutting by using a 3-D finite element model. The phenomena of changing boundary and loading conditions as well as phase changes

during the cutting process were incorporated in the model. Kim (2005) developed a three-dimensional computational model to analyze the evaporative laser cutting process based on steady heat conduction equation with constant cutting velocity. Numerical results of temperature distributions were presented and agreed well with those obtained using semi-analytical methods. Yilbas et al. (2013) presented numerical analysis of the laser cutting of 5 mm thick mild steel sheet which neglected the reflection of laser beam.

To date, there were only a handful of reported analytical or numerical studies on flame cutting process, mainly due to the complication of iron and oxygen combustion. O'Neill and Gabzdyl (2000) presented their theoretical and experimental study on laser assisted oxygen cutting process. Zaitsev and Ermolaev (2014) performed numerical simulation based on elementary assumptions on the iron-oxygen combustion process and verified the results with the observations made with high speed visualization of laser-oxygen cutting process. Zhou et al. (2009) performed numerical and experimental investigations to determine temperature and stress distribution in the flame cutting process. Zhou et al. (2013) established a composite heat source by investigating the interactions of the Gaussian area heat source and the thermogenesis heat source to simulate the flame cutting process. Their numerical results were found to be in good agreement with experiment results. Thiébaud et al. (2014) measured the temperature field in flame cutting of thick steel plate and developed a 3-D simplified numerical model for simulation of temperature field.

Cutting access openings on ship structure is significantly different from a typical plate cutting process because the boundary conditions play an important role. The generation of thermally induced stresses during flame cutting would make it difficult for the subsequent plugging welding process. It is also found that the process inevitably produces negative impacts on structural fatigue

strength and stability. Therefore, one should pay attention on residual stress and deformation in cutting opening process. To our best knowledge, there is no reported study on the residual stress and deformation.

This paper presents the study conducted by using the finite element method to analyze the temperature fields and residual stresses in the cutting opening process. The experimental measurement results were used for the verification of the finite element model. The verified model was then used to study the basic physical parameters for cutting and openings in a ship structure.

2 Numerical simulations

2.1 Model and Material properties

The cutting analysis was carried out first with 3D heat conduction equation to establish the temperature field, which was then used as thermal loading for the subsequent mechanical computation. The finite element code ANSYS was used to conduct thermal structure analysis in the cutting process. A three-dimensional finite element model was developed to calculate the temperature field and residual stress distribution in cutting process accurately. The finite element model was shown in Fig. 1. The same mesh was used in both the thermal and structural analysis. High temperature gradients and stress gradients were anticipated in the vicinity of the cutting line. In order to balance the computation process run-time and numerical accuracy, finer meshes were used in the cutting area and relatively coarse meshes were used in “outer” areas. Transition elements were created to connect the fine and the coarse meshes.

Fig.1 Finite element models for cutting analysis

Fig.2 Material properties of low carbon steel

Material wise, the metal plate was low carbon steel typically used in shipbuilding. Material properties such as thermal conductivity, specific heat, elastic modulus were temperature dependent, and are shown in Fig.2 (Zhou et al., 2014).

2.2 Thermal and mechanical boundary conditions

The process of flame cutting can be divided into four interactive stages.

- (1) The initial cutting point of the metal surface is heated to the ignition point by preheating flame, till the metal combusts under the interaction with oxygen.
- (2) Metal combustion reaction expands to the under layer of the metal.

(3) The slag generated in the combustion reaction is removed, and the metal is cut along the thickness direction.

(4) The cutting notch of the metal is heated to the ignition point by the slag and preheating flame, and then the metal combusts under the action of a stream of oxygen.

In the macroscopic point of view, flame cutting is (a) a chemical process in which the iron (Fe) in the steel is oxidized, and (b) a physical process in which the slag is removed by the oxygen flow stream. The heat source is equivalent to the interaction of the Gaussian heat source and the line heat source in the steel plate. The thermal load of the composite heat source (Zhou et al., 2013) was applied to establish the temperature field. Heat generation rates were applied as "body loads" to represent heat generated by metal combustion. The Gaussian heat source was applied on the top surface to represent the preheat flame. This Gaussian distribution of heat source is expressed as

$$q(r) = q_0 \exp[-Kr^2]$$

where the pointwise distribution, $q(r)$, is expressed by a peak value, q_0 , a width factor, K , and a distance from the centre, r .

An element "birth and death" technique in ANSYS code was used to model the burning of metal. Free convection and radiation boundary conditions were employed together on all surfaces as follows

$$Q_c = \beta(T - T_0),$$

$$Q_r = R_r((T - T_z)^4 - (T_0 - T_z)^4).$$

Where β was the heat transfer coefficient and T_0 was the surrounding temperature. R_r is the radiation constant, and T_z is the absolute zero on the temperature scale used.

In the subsequent mechanical analysis, and to avoid the rigid body movement, the boundary

conditions were set to zero displacement where the metal plate was fully constrained.

3 Verification of the Numerical Model

3.1 Comparison of temperature and stress distribution

Experiments were performed to obtain measurements which would be used to validate the numerical model. Automatic oxygen-cutting machines are used in laboratory and experiments of cutting straight line and cutting circle opening are shown in Fig.3. The coordinate of measurement could be seen Fig.3 (a): X axis is perpendicular to cutting direction and point to right side; Y axis is along the cutting direction. The size steel plate for cutting straight line is 3×1.5 m and the size for cutting circle opening is 1×1 m. The diameter of circle opening is 0.2 m. The thickness of steel plates was 0.022 m, cutting width was 0.004 m, and cutting velocity is 0.006 m/s.

The temperature field was measured using a non-contact temperature measurement method – Infrared Thermography System (Huang and Liu 2007). The resolution of thermal infrared imager is 320 (h) $\times$ 240 (v) pixels, and the range of the operating wavelength is 8 to 14 μm . The temperature range calibrated was from 400 to 1200 $^{\circ}\text{C}$.

The stress field was measured using the impact-indentation stress measurement method, which makes use of the principle of superposition stress fields resulting from the residual stresses and the surface plastic deformation (Lin et al. 2005). The strain change, which is so-called overlap strain increment, caused by an indentation was measured with a biaxial strain-gage. The stress measuring apparatus and strain-gage arrangement in experiment are shown in Fig. 4.

Infrared image of measured temperature field in flame cutting is shown in Figure 5. Figure 6 presents the temperature comparison of measured and numerical results. It can be seen in Fig. 6 that

most of the numerical results were within 12% of the experimental results, and one may conclude that the numerical results were in good agreement with the experimental results.

Fig.3 Experiments of cutting straight line and cutting circle openings

Fig. 4 Stress measuring apparatus and arrangement for strain-gages

Fig. 5 Infrared image of measured temperature field in flame cutting

Fig.6 Comparison of the measured and numerical temperature distributions along the X and Y axis

Fig.7 Comparison of the residual stress along the X axis

Figure 7 depicts the distributions of residual stress on the top surface in the X axis for measured and numerical results. There were three stress measurements arranged along cutting direction, which were perpendicular to cutting line (see Fig.4). It can be seen in Fig. 7 that the residual stress distributions computed using the numerical method proposed herein agreed closely with those determined experimentally. Therefore, one may conclude that the proposed procedure is appropriate for analyzing residual stresses due to cutting.

3.2 Comparison of deformation distribution

Laboratory experiments on cutting straight line and cutting circle opening are shown in Fig.3. The test point arrangements are shown in Fig.8. There were six test points on one side of the straight cutting line, see Fig.8 (a). The displacements of those points were used to measure the deformation during the experiments. For cutting circle opening, those test points were arranged around the circle, see Fig.8 (b). The center of circle was taken as the origin of the coordinate, and the displacements were measured along two directions: radial and tangential directions.

Fig.8 Measurement point arrangement for (a) Linear cutting, and (b) Circular cutting

Table 1 Deformation of straight cutting line

No.	Experiment/mm	Numerical/mm	Difference / %
1-2	-0.02	-0.0170	-15
2-3	-0.03	-0.0270	-10
1-1'	-0.05	-0.0548	10
2-2'	-0.08	-0.0690	-14
3-3'	-0.07	-0.0620	-11

Table 1 shows the deformation measurements obtained for straight line cutting on a flat plate with free (unconstrained) boundary condition. The differences of the experimental and numerical results were less than 15%. It could also be seen that the deformation results were in the same trend.

The deformation of cutting circle opening is shown in Fig.9. It can be seen from Fig.9 that experiment results were slightly higher on certain points. But the results of the experiment and numerical simulation were basically the same.

Fig.9 Comparison of experimental and numerical deformation distribution: (a) Radial deformation, and (b) Tangential deformation.

4 Numerical simulations on different factors in cutting opening process

The findings of the study presented in the previous section demonstrated that the numerical model could simulate well the physical situation of cutting opening process. After it was validated using the experimental results, the numerical model was then possible to carry out a series of simulations to study the basic law of temperature and deformation field in the cutting opening process. Relevant parameters boundary conditions, including plate size, location and shape of the opening were selected and analyzed herein.

4.1 The influence of boundary conditions

The steel plate is rectangular in shape and the size is $2.5\text{m} \times 2.5\text{m} \times 0.022\text{m}$. The four vertices were A, B, C, and D, as shown in Fig.10 (a). Four types of boundary conditions were considered here, and they were:

BC (Boundary Condition)-1

The four edges were constrained in terms of displacement, (four sides welded condition).

BC-2

AB and CD were constrained on three directions of displacement, (two opposite sides welded).

BC-3

AB was constrained on three directions of displacement; C was constrained on vertical

displacement; and D was constrained on the vertical and longitudinal displacement, (One side welded).

BC-4

Point A was constrained in three directions of displacement; B was constrained on the vertical and horizontal displacement; C was constrained on the vertical displacement; and D was fixed in the vertical and longitudinal displacement, (freely support steel plate in a typical cutting process).

Displacement contours are presented in Fig.10. Table 2 and Table 3 show the maximum magnitude of displacement and stress.

Fig.10 Residual displacement corresponding to: (a) BC-1, (b) BC-2, (c) BC-3, and (d) BC-4

Table 2 Largest displacement corresponding to different boundary conditions

Item	Radial /m		Tangential /m		Vertical /m		Overall /m
BC-1	-0.461e-04	0.399E-04	-0.278e-04	0.413e-04	-0.111e-03	0.112e-03	0.114e-03
BC-2	-0.703E-04	0.462E-04	-0.509E-04	0.550E-04	-0.114E-03	0.114E-03	0.117E-03
BC-3	-0.802E-04	0.490E-04	-0.489E-04	0.546E-04	-0.115E-03	0.111E-03	0.118E-03
BC-4	-0.821E-04	0.305E-04	-0.409E-04	0.475E-04	-0.102E-03	0.887E-04	0.111e-03

Table 3 Largest stress corresponding to different boundary conditions

Item	Radial /MPa		Tangential /MPa		Vertical /MPa		Von Mises/MPa
BC-1	-63.8	73.2	-12.4	374	-65.7	25.1	373
BC-2	-61.5	75.2	-21.8	368	-64.2	26.6	369
BC-3	-62.3	72.7	-20.3	368	-65.2	26.6	370
BC-4	-59.9	72.6	-20.5	364	-62.7	26.1	367

As can be seen from the deformation distribution Fig.10, the effects of the boundary conditions on deformation distribution were very obvious. Distortion was mainly distributed to the non-constrain area. For BC-1 (pin constraints on all four sides), steel plate displacement extremes were mainly observed in the vicinity of the hole. For BC-2 (pin constraints at two opposite sides), deformation was distributed to two free edges. For BC-3 (constrained on one side), the distribution was distributed to the free sides. For BC-4 (freely supported), the steel plate distribution was distributed away from the constrained vertex.

From the findings on radial displacement extremes, one may deduce that weaker boundary constraints would create relatively higher displacements. Thermal deformation was much larger at those locations. One can see from the stress contours that high stresses were mainly concentrated around the opening.

4.2 The influence of Plate size

Four steel plates were selected to study the effects of plate size. Length and width of steel plates

were 3.0m×3.0m, 3.0m×2.0m, 2.5m×2.5m and 2m×2m, respectively. The thickness was 0.022m. The diameter of the opening circle was 0.8m. All edges of steel plates were constrained on three directions.

Fig.11 Residual displacements corresponding to different steel plate dimensions: (a) 3.0m×3.0m, (b) 3.0m×2.0m, (c) 2.5m×2.5m, and (d) 2m×2m.

Table 4 Largest displacement corresponding to different steel plate dimensions

Item	Radial /m		Tangential /m		Vertical /m		Overall /m
3.0×3.0	-0.485E-04	0.341E-04	-0.274e-04	0.403e-04	-0.109E-03	0.107e-03	0.113e-03
3.0×2.0	-0.489E-04	0.411E-04	-0.314e-04	0.502e-04	-0.117e-03	0.108e-03	0.121e-03
2.5×2.5	-0.461e-04	0.399E-04	-0.278e-04	0.413e-04	-0.111e-03	0.112e-03	0.114e-03
2.0×2.0	-0.423E-04	0.501E-04	-0.286e-04	0.432e-04	-0.118e-03	0.120e-03	0.122e-03

Table 5 Largest stress corresponding to different steel plate dimensions

Item	Radial /MPa		Tangential /MPa		Vertical /MPa		Von Mises/MPa
3.0×3.0	-62.7	73.0	-13.7	372	-64.7	25.4	372
3.0×2.0	-64.0	72.5	-13.9	376	-65.9	24.5	374
2.5×2.5	-63.8	73.2	-12.4	374	-65.7	25.1	373
2.0×2.0	-65.6	73.4	-11.7	377	-67.4	24.6	376

One may observed from the deformation results that plate dimensions had effect on the stress and deformation distribution and trend. For larger steel plate, for example a 3.0m×3.0m plate, deformation distribution around the opening was more circular. For a smaller steel plate, for example 2.0m×2.0m, the deformation distribution around the openings looks like a square. Similar to the boundary effect analysis, larger steel plates would have weaker constraints. The thermal deformation and stress were observed around cutting openings.

4.3 Influence of opening location

The size of the steel plate was 2.5m×2.5m. The plate thickness was 0.022m. All edges of steel plate were constrained on displacement in three directions. The diameter of opening circle was 0.8m. The variable here was the location of the opening. The steel plate center was set as the origin of the coordinates. The coordinates of opening centers were (0.25,0), (0.75,0) and (0.75,0.75) (Unit in m) , respectively.

Fig.12 Residual displacements corresponding to: (a) Center (0.25,0), (b) Center (0.75,0) and (c) Center (0.75,0.75).

Table 6 Largest displacement corresponding to different opening locations

Item	Radial /m		Tangential /m		Vertical /m		Overall /m
(0,0)	-0.461e-04	0.399E-04	-0.278e-04	0.413e-04	-0.111e-03	0.112e-03	0.114e-03
(0.25,0)	-0.488E-04	0.470e-04	-0.266e-04	0.448e-04	-0.115e-03	0.114e-04	0.117e-03
(0.75,0)	-0.543E-04	0.102e-03	-0.383e-04	0.531e-04	-0.150e-03	0.149e-03	0.163e-03
(0.75,0.75)	-0.587E-04	0.104e-03	-0.457e-04	0.536e-04	-0.151e-03	0.153e-03	0.166e-03

Table 7 Largest stress corresponding to different opening locations

Item	Radial /MPa		Tangential /MPa		Vertical /MPa		Von Mises/MPa
(0,0)	-63.8	73.2	-12.4	374	-65.7	25.1	373
(0.25,0)	-63.3	73.8	-14.2	-375	-65.3	25.0	373
(0.75,0)	-62.7	73.9	-12.0	-392	-64.7	22.8	388
(0.75,0.75)	-61.0	74.8	-11.8	-395	-62.8	26.8	389

There was an obvious trend that distortion was away from the constrained boundary. When the opening was located closer to the boundary, the residual displacement and residual stress increased slightly. The peak values of deformation and stress were mainly observed in the vicinity of the cutting edge as expected.

4.4 Influence of the shape of openings

The plate size was 2.5×2.5m. Plate thickness was 0.022m. All edges of steel plate were constrained on displacement in three directions. Four types of openings at the center of the plate were used, and they were circular, manhole (oval), square and square with chamfered corners, respectively.

The diameter of circle was 0.8m; the dimension of manholes was 0.4 × 0.8m; edge length of square was 0.8 × 0.8m; and it was the same square openings with chamfered at a radius of 0.1m.

Fig.13 Residual displacement corresponding to various shape of opening: (a) circular, (b) Manhole (oval), (c) Square and (d) Square with chamfer

Table 8 Largest displacement corresponding to different opening shapes

Item	Radial /m		Tangential /m		Vertical /m		Overall /m
Circle	-0.461e-04	0.399E-04	-0.278e-04	0.413e-04	-0.111e-03	0.112e-03	0.114e-03
Manhole	-0.978E-04	0.335 e-03	-0.330e-03	0.284e-03	-0.222e-03	0.235e-03	0.399e-03
Square	-0.311E-03	0.194e-03	-0.244e-03	0.254e-03	-0.193e-03	0.194e-03	0.348e-03
Square with chamfer	-0.717e-04	0.417E-04	-0.875e-04	0.751e-04	-0.112e-03	0.129e-03	0.156e-03

Table 9 Largest stress corresponding to different opening shapes

Item	Radial /MPa		Tangential /MPa		Vertical /MPa		Von Mise/MPa
Circle	-63.8	73.2	-12.4	374	-65.7	25.1	373
Manhole	-35.8	192	-71.4	-391	-56.9	48.5	424
Square	-28.4	905	-55.7	-1660	-145	702	912
Square with chamfer	-33.9	132	-29.5	369	29.1	24.9	373

It can be seen from the deformation and stress contours that the residual deformation and stress were concentrated in the vicinity of plate openings. The deformation distribution of circular opening was more uniform. The deformation distribution of manhole was mainly along the perimeter of the opening. The deformation of square hole was mainly concentrated at the four corners. The chamfer arrangement appeared to reduce the deformation by half. From the stress extremes, the smoother opening curve appeared to yield smaller residual stress. In terms of the magnitude of stress extremes and order from low to high stress were circle, manhole and square hole. It can be deduced from the simulation results that the cutting and opening should utilize smooth curve without any significant chine [sharp change in angle]. For a square opening, the residual deformation and residual stress were found to be 2.2 – 2.4 times of those with chamfer, respectively. Thus, chamfering is an effective method for reducing stress and deformation in cutting and openings.

5 Simulation of cutting and opening in ship deck

Ship deck was taken as an example to conduct the simulation of cutting and openings. The opening was 400mm×800mm. Based on earlier findings, chamfering process was adopted in the cutting and opening design. The specification of deck structure model was as follow:

Sizes of deck structure	1120×900	mm
Thickness of deck sheet	10	mm
Deck longitudinal member	6 × 80	mm
Deck transverse member	10×100	mm
Sizes of opening	400×800	mm
Chamfer of opening	50	mm

The FEM model of deck structure is as shown in Fig.1. In the thermal analysis, free convection and radiation boundary conditions were satisfied on all surfaces. In the subsequent mechanical analysis,

and to avoid the rigid body movement, boundary conditions were set to zero displacement at four sides of the deck plate, i.e. they were pinned and constrained. The numerical simulation results of residual displacements and residual stresses were indicated in Figs 14 and 15, respectively.

Fig14 Residual displacement at (a) UX, (b) UY, (c) UZ and (d) USUM.

Fig.15 Residual stress in the form of (a) SX stress, (b) SY stress, (c) SZ stress and (d) SEQV stress.

The main thermal deformations were observed along the cutting edge. The thermal deformation was quite small and the displacement extreme was 0.3mm. In terms of shipbuilding engineering precision, these deformations were acceptable.

The maximal magnitude of residual stress in X axis was 384 MPa; the maximal magnitude of residual stress in Y axis was 438 MPa; and the maximal magnitude of Von-Mises stress was 301 MPa. The thermal stresses of cutting were closed to the yield stress. It can be seen from Fig. 15(d) that the stresses were dispersed over a very narrow area along the cutting edge. One may conclude that the approach described herein should not have a significant effect on the safety of structure.

6 Conclusions

A numerical simulation study was performed to analyze the thermo-mechanical behavior of creating a cutting opening in the ship hull using flame cutting. The salient points obtained in this work are summarized below.

- 1) Structural boundary conditions, plate size and the location, size and shape of the opening have significant impact on the distribution of deformation and stress in the steel hull. Weaker structural constraints would create relative larger distortion.
- 2) Chamfering treatment on a rectangular or square hole greatly reduced residual stress and

deformation. The study shows that chamfering alone reduced the deformation and stress by about 2.2 times and 2.4 times, respectively, demonstrating that chamfering is an effective method in the cutting process.

3) The study showed that creating opening on a ship hull using flame cutting produced relatively small displacement of less than 0.3mm, and the extreme of Von-Mises stress was 301 MPa, and the stress zone was limited to a narrow strip along the cutting line. The findings showed that creating a designed opening in the ship hull through flame cutting should not have a significant effect on the safety of the ship structure.

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