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Yard trailer routing at a maritime container terminal

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ABSTRACT

This paper addresses the trailer routing problem at a maritime container terminal, where yard trailers are normally assigned to specific quay cranes until the work is finished. A more efficient trailer assignment method called "dynamic routing" is proposed. A heuristic was developed and a wide variety of computational experiments were conducted. The results of the experiments demonstrated that the dynamic routing reduces travel distance and generates substantial savings in the trailer fleet size and overall cost (15% reduction). The paper's contribution to the literature is the development of a new routing scheme achieving container handling cost savings for a terminal.

Keywords: Container transportation; Vehicle routing; Cargo handling; Heuristic; Mathematical programming

1. Introduction

Due to the continuously increasing container trade, many terminals are presently operating at or close to capacity. In addition, considering the trend towards larger container ships, the need for efficient terminal operations is more important than ever. An efficient terminal is one that facilitates the quick transshipment of containers to and from ships.

The efficiency of a maritime container terminal depends on the smooth and efficient handling of containers. There are three basic types of container handling systems engaged in loading and discharging operations at a container terminal: chassis, straddle-carrier and transtainer systems, the latter being the most popular in major terminals due to the need for high container storage capacity in the yard. For the transtainer system, there are several types of handling equipment employed such as quay cranes, yard gantry cranes and yard trailers. The bottleneck in the loading and discharging occurs at the quay crane operation. Quay cranes should not halt their working process by waiting for trailers to come to pick up containers from them or to deliver containers to them. In order to prevent such unproductive idling, a sufficient fleet size of yard trailers is generally deployed.

At a dedicated container terminal, a set of trailers is usually assigned to a specific quay crane until the work is completed. In this process, trailers return to the crane after delivering the containers. Such a static assignment policy is also widely applied for multi-user container terminals. At a multi-user terminal, ships are usually berthed relatively close to their container storage in the yard for quicker container transshipment to and from the ships. However, in order to increase the usage of quay space in berthing ships, some ships may be assigned to a quay location far from their container storage. As mentioned previously, the bottleneck in the transshipment operation occurs in the quay crane operation. In order not to keep the quay cranes idle, a set of yard trailers continuously delivers containers to and from the assigned quay crane without interruption. Such a static assignment of trailers is less flexible in its trailer usage. To do this effectively, more trailers should be deployed especially when the ship is berthed far from its container storage area. This can be a serious cost issue, especially if a set of trailers is permanently assigned to a specific quay crane as done at a dedicated terminal. This leads to the purchase of a large fleet of trailers to cope with the worse case scenario in terms of ship location at the quay, although the terminal has plenty of redundant trailers when all ships are berthed close to their container storage location.

In light of the inefficiency involved in the static trailer assignment, another approach may be more advantageous, such as: when a trailer arrives at a container stack point in the yard after receiving a container from a quay crane under discharging operation, instead of going back to the quay crane which is situated far from the present location, it proceeds to the next stack point which is close to the present location, to receive a container for export, and then proceeds to another quay crane under loading operation. Such a dynamic trailer routing may reduce the fleet size of trailers without increasing the overall dwell time of the ship in port, thereby minimizing unproductive empty travel. However, terminal operators do not seem to prefer the dynamic routing because of the possibility of human error in the delivery process of containers that may be caused by the routing complexity.

Optimizing yard trailer routing helps reduce the trailer fleet size, without increasing the ship's port dwell time, thus saving considerably capital and operating costs. The effect in fleet size reduction may be more significant when a multi-trailer system, having a capacity of more than one container, is employed. The downsizing of the trailer fleet could be much greater if dynamic routing of multi-trailers is performed, e.g., a multi-trailer with five import containers delivers one container first, picks up one export container, delivers three import containers, picks up two containers, delivers the last import containers, and finally takes the exported containers on it to a quay crane.

This study is concerned with the dynamic trailer routing mainly for a multi-user terminal. In the next section we present the literature review. Section 3 formulates several problems, all related to the trailer routing, while in Section 4 a solution method employing a genetic algorithm is described. In Section 5 a variety of computational experiments are conducted, which demonstrate the effectiveness of the algorithm in decreasing trailer travel distance and consequently trailer fleet size. The final section concludes the paper.

2. Literature review

The yard routing problem falls in the category of the vehicle routing problems and more specifically, it has characteristics of backhaul due to the pickup and delivery processes involved in the problem.

The vehicle routing problem with backhauls (VRPB) finds an optimal set of orders (or routes) of deliveries (or linehauls) and pickups (or backhauls) for vehicles departing from a particular depot, where in each route, pickup loads are carried on the return trip after all deliveries have been made.

There are variants to the VRPB. Some of them are related to this problem. One of them is the so-called pickup and delivery problem (PDP), which differs from the VRPB in that pickups are not necessarily carried out after all deliveries are finished. Dumas et al. (1991) develop an exact algorithm for a single vehicle version of the PDP with time window constraints. They also describe an extension of their approach for solving multi-vehicle problems (i.e., the PDP with time windows), which however, has not been implemented. Nanry and Barnes (2000) exploit a tabu search-based heuristic for the PDP with time windows. Recently, Wang and Regan (2002) consider a multiple traveling salesman problem with time windows in order to identify a minimum cost solution of a pickup and delivery problem with backhauls. These studies differ from the problem under examination in this paper, which deals with pickup and delivery with multiple tours that are independent and not connected at a depot like the PDP.

In another variant of the VRPB, Min et al. (1989, 1992) describe a multi-depot version of the VRPB. Their heuristic approaches the problem in three steps: (1) aggregation of pickups and deliveries into clusters; (2) assignment of clusters to depots and routes; and (3) routing vehicles. Hall (1991) creates and evaluates spatial models for the VRPB with multiple depots. Jordan and Burns (1984) consider a backhaul problem with two depots, where only one backhaul load to a depot can be serviced after one linehaul from the other depot. In their study, each depot has multiple customers each of whom must be serviced independently unlike the vehicle routing problem. Thus, the structure of the routing can be referred to as the *single stop route*. They propose a greedy algorithm that optimally matches empty vehicles to form backhaul loops. Jordan (1987) extends their problem for a routing system with more than two depots. Ball et al. (1983) propose simple greedy heuristics especially tailored for bulk pickup and delivery routing by jointly using a fleet of private vehicles (actually long-leased fleet) and an outside carrier. Each pickup is coupled with its destination and no other pickup and/or delivery points are visited in-between. Every route services a set of these pickup and delivery pairs. As each private vehicle has a time constraint (or a sort of time capacity) for servicing the customers, additional private vehicles or the contract carrier carries out any excess workload that might emerge. This problem has only a minor relation to the backhauling since pickup and delivery in a pair are not separable; therefore by resembling the pair as a customer it could be referred to as the vehicle routing problem with time constraint. Fisher et al. (1995) develop a network flow-based heuristic for a pickup-delivery problem that is similar to Ball et al. (1983). The above-mentioned variant of the VRPB is different from this problem in that the latter deals with multi-trailers that permit the mixture of pickup and delivery in a tour.

Very few studies have been conducted in the past for routing problems present at maritime container terminals. They usually address routing problems of the automated guided vehicle (AGV), straddle carrier and transfer crane. Given that the AGV has a common feature with the yard trailer of one container capacity and runs much slower than the yard trailer, the fleet size of the former is larger than the latter. This produces heavy traffic of the AGVs and therefore the proper handling of this traffic is crucial. Evers and Koppers (1996) develop a hierarchical AGV control system by using semaphores. Vis et al. (2001) develop a heuristic based on the maximum flow problem to determine the fleet size of AGVs with the dynamic job assignment policy like this study. They define the time when a job takes place for transferring a container from one place to another, in order to construct an underlying flow network; therefore in real application such a job definition process likely becomes troublesome due to a huge size of the network. In addition, their model cannot be applied for the job assignment to trailers with more than unit capacity like this study. Bish (2003) proposes the similar dynamic job assignment to the AGVs, carrying out the worst-case analysis by a heuristic developed for the AGV assignment problem. His aim is to minimize the turnaround time of ships, while our objective is to reduce the trailer fleet size.

Routing problems are also present in straddle carrier operations. The straddle carriers, characterized as being a mixture of a yard trailer and a transfer crane, are employed in loading and discharging of containers to/from ships, handling empty container inventory and delivering containers to trains at an on-dock rail yard. As the straddle carriers are engaged in such complicated and different types of container handling, their efficient routing is attained through the minimization of empty runs. Steenken et al. (1993) address a routing problem of multiple straddle carriers engaged with time window of tasks involved in the system. Their study is similar to this problem in terms of multiple tours being formed; however their routing is much simpler than the one under examination due to the single capacity of straddle carrier. Kim and Kim (1997) and Kim and Kim (1999b) deal with a problem of straddle carrier whose role is different from Steenken et al. (1993). Straddle carriers in the two Kim and Kim studies are only utilized for container handling in container storage areas in the yard like transfer cranes. They aim to minimize the total distance that a single straddle carrier travels. Kim and Kim (1999a) and Kim and Kim (1999c) consider routing of a single transfer crane in handling containers in stack areas of the yard. Therefore, their studies are basically the same as Kim and Kim (1997) and Kim and Kim (1999b).

3. Problem formulation

In a multi-user terminal, numerous vessels arrive at and depart from the terminal at different times. The trailer routing that is addressed in this paper, is defined with a given set of calling vessels in port at a time, as shown in Fig. 1. For instance, routing 1 involves three vessels under handling operation: all ships 1, 2 and 3 in discharging, while routing *n* is concerned with two ships: ship 4 in loading and ship 6 in discharging. New routing decisions are therefore made, every time a ship changes its operating tasks such as at the start of loading or discharging.

Fig. 1

Fig. 2 illustrates nodes involved in handling operation at a terminal. This example includes three quay cranes (one in discharging and two in loading) and nine container stack points in the yard (nodes in the box of dotted line). A fleet of trailers has a set of tours connecting the cranes and stack points.

Fig. 2

For the sake of simplicity we consider only 40-ft. containers, even though there is diversity in containers used for sea-borne transportation. The trailers used in the terminals are in most cases capable of carrying only one container, while trailers with capacity of more than one container are seen in very few modern terminals such as the ECT in Rotterdam. The former is hereafter referred to as *single-trailer* and the latter as *multi-trailer*.

The itinerary of a single-trailer consists of picking up a container at a quay crane in discharging (referred to as CD), delivering it to an assigned stack area for discharged containers (referred to as AD) and returning to the CD. This itinerary, called *static*, forms a shuttle transit between the two locations: shipside and land-side ones. The trailers are kept in charge of container transshipment between these two assigned places until all the relevant work is finished. For more *dynamic* usage, after the delivery to the AD it may go to another CD or a stack area for export containers (referred to as AL) to move a container to a quay crane in loading operation (referred to as CL).

A multiple-trailer picks up, in a *static* itinerary, multiple containers at a CD to deliver them to one or more ADs, and then goes back to the CD. In order to increase trailer productivity more *dynamic* itinerary courses may be considered:

- pick up containers at a CD, deliver them to ADs, and go to another CD
- after moving containers from a CD to ADs, go to ALs
- after picking up at a CD, go to ADs and proceed to a CL

In this section, we formulate the dynamic itinerary for both single- and multi-trailers. For easier understanding, we first formulate a simpler case, i.e., the single-trailer problem (STP) and next a more complicated one, i.e., the multi-trailer problem (MTP).

3.1. Single-trailer problem formulation

The STP produces more than one tour (or cycle) of trailer in loading/discharging operations. This resembles the single-depot or multi-depot vehicle routing problems, but with the difference that it does not have more than one tour emanating from the depot(s), which is the equivalent of quay crane in this case. The trailer routing problem that we are addressing aims to form a set of tours at a time, like the vehicle routing problem. In other words, we focus on the tours pertaining to one cycle operation of the quay cranes. Quay cranes iterate a loading or discharging process many times, each time a single trailer leaves or arrives at a crane. The problem is concerned with routing pertaining to every crane in the entire operation. In this context, the tours are not to be overlapped at the quay cranes. This characteristic encourages us to utilize the assignment problem, which is a relaxed problem of the traveling salesman problem and yields one or more tours for a routing problem in which each node is visited only once.

There is a restriction of precedence associated with the trailer routing problem, that is, a loaded trailer must first deliver its container before going to the next location whether it is a quay crane or a stack area, and an empty trailer must not go to a CL or an AD. One reason for this is quick container movement and the other is trailer capacity.

Taking into account the similarity to the assignment problem, the STP may be formulated as follows:

[ST1] Minimize $\sum_{i\in P}\sum_{j\in P} C_{ij}x_{ij}$ (1)

subject to $\sum_{i\in P} x_{ij} = 1 \quad \forall j \in P,$ (2)

$\sum_{j\in P} x_{ij} = 1 \quad \forall i \in P,$ (3)

$x_{i,T^i} = 1 \quad \forall i \in S,$ (4)

$x_{ij} \in \{0,1\} \quad \forall i, j \in P,$ (5)

where

P : set of points that trailers visit

$S \subset P$: set of points that trailers receive containers (referred to as *origin points*)

C_{ij} : distance from points i to j

T^i : destination point for origin point i

x_{ij} : =1 if a trailer travels from points i to j, =0 otherwise

The decision variables are x_{ij} s. The objective function (1) is the minimization of total travel distance. Constraint sets (2) and (3) ensure that every point must be visited exactly once and must be involved in a tour. Constraint set (4) guarantees that a loaded trailer delivers its container before visiting someplace else. It also assures that an empty trailer does not visit a destination (or delivery) point before it picks up a container from a point of origin, since the constraint set has already assigned a container delivery to the associated destination.

3.2. Improved single-trailer problem formulation

We present another formulation to the STP. When using trailers with a single container capacity, a trailer must go to the delivery point after picking a container from an origin point. Consequently, in determining a tour of a trailer, there is only one option for loaded legs of the tour. In this context, forming tours of trailers is reduced to a construction of tours visiting nodes where each corresponds to an origin-destination point pair.

With this concept, the STP may be formulated as follows:

$$\text{[ST2]} \quad \text{Minimize} \quad \sum_{i \in P} \sum_{j \in P} D_{ij} u_{ij} \tag{6}$$

$$\text{subject to} \quad \sum_{i \in P} u_{ij} = 1 \qquad \forall j \in B, \tag{7}$$

$$\sum_{j \in P} u_{ij} = 1 \qquad \forall i \in B, \tag{8}$$

$$u_{ij} \in \{0,1\} \qquad \forall i, j \in B, \tag{9}$$

where

B : set of movements of container between yard stack areas and quay cranes

D_{ij} : distance from the destination of container movement i to the origin of container movement j

u_{ij} : =1 if a trailer travels from the destination of container movement i to the origin of container movement j, =0 otherwise

The decision variables are u_{ij} s. The objective function (6) is the minimization of total travel distance. Constraint sets (7) and (8) ensure that every movement must be serviced exactly once and must be involved in a tour. Interestingly, formulation [ST2] is a classical assignment problem, which defines the solution easily with an efficient solution method such as the Hungarian method.

3.3. Multi-trailer problem formulation

The MTP does not permit the same treatment of the origin-destination movements as the formulation [ST2], since a trailer visits more than one destination after an origin point. Thus, origin and destination points need to be treated separately like the formulation [ST1]. More important than the formulations [ST1] and [ST2] is the trailer capacity constraint in the MTP. Assuming each quay crane loads and discharges the same number of containers at a time, no capacity restriction virtually emerges if a trailer moves containers from ALs to a specific CL after finishing a set of deliveries from a CD to ADs. This is usually the case in most container terminals, as a whole stack area is partitioned into two parts: one for import (i.e., AD) and the other for export (i.e., AL), imposing a long movement of a trailer between AL and AD due to the rectilinear form of trailer movement allowed (refer to Fig. 6 in the Section 5), even if specific export and import containers are situated side by side. It is obvious that this stack area layout does not allow forming mixed itineraries of delivering export-containers and picking up import-ones.

In this study, we introduce more flexible itineraries of trailers, for example the mixture of delivery and pickup, as it may be applicable in the near future when innovative material handling systems are developed. Nevertheless, it is assumed that a multiple-trailer visits a CD to pick up containers after it delivers all containers to a CL.

The MTP may be formulated as follows:

[MT] Minimize $$\sum_{i \in P} \sum_{j \in P} C_{ij} x_{ijk} \qquad (10)$$

subject to $$\sum_{i \in P} \sum_{k \in H} x_{ijk} = 1 \qquad \forall j \in P, \qquad (11)$$

$$\sum_{j \in P} \sum_{k \in H} x_{ijk} = 1 \qquad \forall i \in P, \qquad (12)$$

$$w_{jk} = \begin{cases} 0 & \forall j \in Q^D, k \in H \\ \sum_{i \in P} \left(w_{ik} + V^i\right) x_{ijk} \le U^k & \forall j \in P\left(\neq Q^D\right), k \in H \end{cases}, \qquad (13)$$

$$y_{ik} = \sum_{j \in P} x_{ijk} \qquad \forall i \in P, k \in H, \qquad (14)$$

$$\sum_{k \in H} k y_{ik} = \sum_{k \in H} k y_{jk} \qquad \forall i \in Q, j \in S^i, \qquad (15)$$

$$x_{ijk} \in \{0,1\} \qquad \forall i, j \in P, k \in H, \qquad (16)$$

$$y_{ik} \in \{0,1\} \qquad \forall i \in P, k \in H, \qquad (17)$$

where

P : set of points that trailers visit

H : set of trailers

Q : set of quay cranes

$Q^D(\subseteq Q)$: set of CDs

C_{ij} : distance from points i to j

S^i : set of container stack points relevant to quay crane i

V^i : container volume handled at point i

(>0 if trailers pick up containers at i, <0 if they deliver)

U^k : capacity of trailer k

x_{ijk} : =1 if trailer k travels from points i to j, =0 otherwise

y_{ik} : =1 if point i is serviced by trailer k, =0 otherwise

w_{jk} : container volume on trailer k immediately before visiting point j

The decision variables are x_{ijk} s and y_{ik} s. The objective function (10) is the minimization of total travel distance. Constraint sets (11) and (12) ensure that every point must be visited exactly once and involved in a tour. Constraint set (13) guarantees that the trailer capacity is satisfied every time a multi-trailer picks up containers at an origin point. Note $w_{jk} = 0$ at discharging cranes ensures the assumption of empty multi-trailer movement destined to CDs. Equality sets (14) and (15) assure that a trailer that has picked up containers at a CD, must deliver them to its relevant stack points and that a trailer ought to deliver containers that have been picked up at its dedicated stack points. In other words, origin points and the relevant destination points are involved in a particular tour.

4. Solution procedure

As stated in the previous section, the single-trailer problem can be reduced to the classical assignment problem that easily defines an optimal solution. Meanwhile, an efficient exact solution procedure is not known for the multi-trailer version of the problem. This guides us to develop a heuristic method to nearly optimize the solution by using a genetic algorithm (GA).

4.1. Outline of the solution procedure

GAs represent a powerful and robust approach for developing heuristics for large-scale combinatorial optimization problems. GAs imitate the process of evolution on an optimization problem. Each feasible solution of a problem is treated as an individual whose fitness is governed by the corresponding objective function value. A GA maintains a population of feasible solutions (also known as *chromosomes*) on which the concept of the survival of the fittest, among structures, is applied. There is a structured yet randomized information exchange between two individuals (*crossover* operator) to give rise to better individuals. Diversity is added to the population by randomly changing some genes (*mutation* operator). A GA repeatedly applies these processes until the population converges.

The procedure of GA is outlined in Fig. 3. In this figure, the objective function value and solution alternatives of the MTP correspond to the fitness value and individuals, respectively. For our heuristic the number of individuals in a generation is set at 20.

Fig. 3

4.2. Representation

Instead of using the classical binary bit string representation, the chromosomes are represented as character strings. Fig. 4 states the formation of tours for a trailer fleet.

Fig. 4(a) is the demand (or container volume) at nodes where the positive values correspond to pickup while the negative values imply container delivery. The demand is distributed to the cranes with which it is associated.

Fig. 4(b) illustrates a typical chromosome representation of an MTP throughout the entire GA process. The length of the string of digits is the number of points of container delivery and pickup involved in the handling operation. The chromosome is constructed in such a way that the leftmost cell is assigned to a CD, allocating figures in order of visit towards the rightmost location. Furthermore, the chromosome has a table with it, revealing the container volumes that multi-trailers pick up and deliver, where positive values indicate pickups while negative values define deliveries.

As shown in Fig. 4(c), a set of feasible tours of multi-trailer is formed by examining the chromosome and associated container volume table in the following way: given the multi-trailer capacity, a multi-trailer carries out pickup and delivery by looking at digits in cells from left to right. If the process encounters cells whose container volume violates the capacity restriction, it skips them. The resulting set of cells processed forms a tour. If unprocessed (or skipped) cells exist, another multi-trailer starts the same process for those cells. This process is iterated until no unprocessed cells are left. This procedure assumes a sufficiently large size of multi-trailers available to cover all the cell demand.

Fig. 4(d) shows the resulting tours being formed. The geographical representation of the tours is presented in Fig. 5.

Figs. 4 & 5

4.3. Fitness

A selection criterion is used for picking the two parents to apply the crossover operator. The appropriateness of a selection criterion for a GA depends on the other GA operators chosen. A typical selection criterion gives a higher priority to fitter individuals and this leads to a faster convergence of the GA. The MTP is a minimization problem; thus, the smaller the objective function value is, the higher the fitness value must be. For this, the fitness function can be defined by the reciprocal of objective function as done in Kim and Kim (1996). Another alternative is a sigmoid function as used in Nishimura et al. (2001) for a GA heuristic so as to find a near optimal solution to a berth allocation problem, where multiple vessels may be served at a specific berth. The former was selected for the MTP, based on the result of a preliminary experiment.

4.4. Crossover

The crossover scheme is widely acknowledged as critical to the success of GA. The crossover scheme should be capable of producing a new feasible solution (or child) by combining good characteristics of both parents. Preferably, the child should be considerably different from each parent. As examined in Ahuja et al. (2000), we tested two sophisticated crossover schemes: *path crossover* and *optimized crossover*. According to our preliminary computational tests, the path crossover showed better overall results; we consequently apply it throughout the experiments. For more detail of crossover procedure for the MTP, we refer to Nishimura et al. (2001).

4.5. Mutation

Mutation introduces random changes to the chromosomes by altering the value of a gene with a user-specified probability called *mutation rate*. In our application, if mutation is to occur in a gene, we generate two random numbers between 1 and the string length, which define positions within the chromosome. The value of a gene at these two positions are interchanged, thereby changing the order of loading sequence, to create a new chromosome. Based on our preliminary experiments, the mutation rate was set to 0.05.

5. Computational experiments

5.1. Experimental design

The solution procedure is coded in “C” language on a Sun SPARC-64GP workstation. The experiments were designed systematically, defining 32 problems based on the combination of the factors presented in Table 1.

Table 1

Since our purpose is to investigate the potential efficiency of dynamic trailer usage especially at multi-user terminals, we assume relatively long quay length with four or six berths as presented in the table. Four-berth terminal represents a medium size of hub port such as port of Colombo in Sri Lanka, while six-berth terminal reflects a mega hub port such as the ECT in Rotterdam. Trailer capacity settings are defined by taking into account a wide variety of trailer types including the fact that the ECT of Rotterdam employs a fleet of multi-trailers, each capable of carrying six 40-ft. containers.

The container storage arrangement in a yard depends highly on the export and import throughput of the terminal. For the experiments conducted, two typical types of stack arrangement are assumed as illustrated in Fig. 6. Type 1 spreads containers out in the whole storage area while type 2 intensively locates containers of a specific ship in blocks behind a berth. Note that for type 2, the ship is not always allocated to the berth close to its container blocks when the terminal is busy with plenty of calling ships; thus random berth-to-ship allocation is assumed in the experiments. In type 1, as containers are spread over a lot of blocks, the operator may have to perform a complicated planning for a suitable arrangement of the storage locations for different ships. Type 2 may better facilitate container management due to its dense storage. However, this arrangement scheme may be physically impossible in the case where a number of ships are scheduled to call and be served sequentially in a short time period, thereby resulting in shortage of container blocks behind a particular berth. Observing the computational results for two such different storage arrangements, we may have some implications regarding the relationship between the storage arrangement and the efficiency in trailer usage.

As shown in Fig. 6, storage areas for export containers are in general located on the dock side (upper four rows of the container block), while those for import are on the land side (lower four rows of the container block). Trailer traffic moves along the arrows in the figure. A box corresponds to a block of containers stacked on the yard. Directly behind each berth, there are 16 blocks with a small corridor situated vertically between two columns of blocks. A wider corridor is vertically established between two groups of 16 blocks just below each berth. Trailers can move upwards and downwards in these corridors, while they can run only leftwards in horizontal corridors. This trailer traffic scheme is reflected in the practice of some container terminals in Japan. Note that the trailers run in the narrower corridors despite the fact that no arrows are displayed in the figure.

Fig. 6

Ten computational samples are randomly generated for each computational problem, in order to incorporate the nature of diversity in stack point location and berth location where the relevant ship is handled, as both affect the resulting route length. In addition, the type of handling operation (i.e., loading or discharging) and the handled amount of containers associated with the ship are randomly defined. A ship handles the total of import and export containers, ranging from 300 to 1100, with the number of storage points in a yard, P, ranging from 5 to 10. Typical storage points are plotted in the two different types of storage arrangements in Fig. 6. Two quay cranes are assigned to a ship with less than totally 500 import and export containers whereas three cranes are engaged with no less than 500 containers. Due to the lack of relevant data, the container quantity handled by a ship and the location of its storage point in the yard are generated randomly based on the uniform distribution. For stack arrangement type 2, the storage points are located randomly within blocks assigned to the relevant ships. The figures for P and Q are based on some surveys in container terminals in Japan.

In each computation, every quay crane loads or discharges a batch of six containers at a time (not necessarily simultaneously). In computations with trailer capacity of less than six containers, more than one trailer must be assigned to each crane. This is contradictory to the problem formulations of the STP and MTP, since the formulations allow only one trailer to visit any of the quay cranes at a time. We deal with this issue by defining multiple virtual cranes for each existing crane, where the number of virtual cranes depends on the trailer capacity. This poses the question as to which virtual crane handles which containers out of the six. To solve this, we employ the so-called "Clark and Wright's Saving method" (Clarke and Wright, 1964) that composites preliminary routes from each crane to storage areas for the associated containers to handle. Based on the obtained set of routes, we assign the containers to every virtual crane. In the case of the trailer capacity of three containers with eight existing quay cranes, the problem to be solved has 16 virtual cranes, each with three containers being assigned according to the above-mentioned procedure.

The direct aim of the dynamic yard trailer assignment (or itinerary) to a quay crane is to shorten travel distances of the trailers in ship handling tasks. In order to investigate how the dynamic assignment is effective, we first look at dynamic yard trailer itineraries at a given moment of time in the entire operation. The dynamic assignment may perform to reduce the number of trailers by the reduction of travel distance in the situation where for a long operational time of a terminal, trailers work for a different number of ships at a time with the various amount of containers handled. Therefore, we next get into the details on the effect of the dynamic trailer assignment in more comprehensive handling circumstances, as for example when several ships arrive sequentially at the terminal and discharge/load various amount of containers before departure. By this analysis we examine if the proposed routing principle achieves savings in travel distance and consequently in trailer fleet size in the longer time span. The GA we employed for the dynamic assignment is a heuristic that does not guarantee that the resulting solutions are optimal. To see how the GA performs, as the next analysis we compare solutions between the formulations [MT] and [ST2] for the problems associated with the unit capacity of the trailers.

5.2. Reduction of travel distance by the dynamic trailer assignment

As stated in Section 1, container terminals usually employ the static trailer itinerary in that a set of trailers is permanently assigned to a specific quay crane. This forces a trailer to return to the assigned crane after delivery of containers to storage areas, generating unproductive empty runs to the crane. Computing the reduction rate of route length in Eq. (18), we compare the static and dynamic itineraries in terms of total distance covered by the trailers in various cases as presented in Table 2. Note that this analysis is not concerned with the number of trailers needed. In other words, we are interested in the total travel length of trailers for one cycle of container handling of all the ships being served at the same time in the terminal, with the assumption that there is a sufficient number of trailers available.

$$(TS - TD)/TS \times 100 \tag{18}$$

where TS is the distance of the static itinerary while TD is the one of the dynamic itinerary.

Table 2

Note that while the GA procedure was employed to obtain the numbers in the dynamic itinerary, a simple calculation was only required for the static itinerary. Also note that in the dynamic cases, the formulation [ST2] was utilized for single trailers (or unit trailer capacity), whereas the formulation [MT] was for multi-trailers (or more than single capacity).

Table 3 shows the average reduction rate in the 10 computation samples for the 32 problems. As can be seen from the table, the distance reduction rate grows as trailer capacity is decreased. Surprisingly, negative values are observed for the cases with six-container capacity. This implies that the static assignment is better than the dynamic one. In such cases the reduction rate is supposed to be null, since an optimal solution identified by [MT] for the dynamic assignment with multi-trailers should result in a static assignment. However, as the GA is a heuristic, it produces a dynamic assignment as a near optimal solution where TD is greater than TS, thus resulting in negative reductions in distance.

Table 3

It is noted that the greater distance reductions are observed in the cases where the capacity is small. This is due to the fact that the container storage is relatively spread over the container stacks regardless of the stack arrangement, thereby increasing the distance that the loaded trailers travel. Therefore, for the MTP, each trailer has a limited opportunity to reduce its empty travel length in the static itinerary. On the other hand, lower capacity trailers will have long empty runs when their operation is based on the static itinerary. Consequently, the dynamic itinerary results in enormous savings in empty runs. As regards the diversity in the reduction rate over the different computational settings, the problem cases with six berths realize slightly more distance savings than the four-berth problem cases. It is notable that there is no significant difference in distance reduction between arrangement types 1 and 2.

5.3. Savings in travel distance and trailer fleet size

The above experiments pertain to the problems associated with the loading and discharging tasks at a time (called single span planning) when a given set of ships is being served. The distance analyzed is the one observed at that moment. However, the terminal carries on the tasks of ship handling for a long period of time, a week, a month, even a year without interruptions, accommodating in sequence the ships that arrive in the port. The short-term planning objective of yard trailer assignment is the minimization of the travel distance, while from the viewpoint of the long-term decision-making, efficient planning results in the minimization of the number of trailers required. In order to examine the impacts of the latter, we next analyze the multiple span problems where the handling tasks of several ships continue in sequence for a long period of time during which some changes occur in the handling tasks of a specific ship. The change of tasks can be described as follows: Referring to Fig. 1, suppose three ships are under a discharging operation. This state composes one planning phase (or span). In a few hours, one of them finishes discharging and then starts loading. This state continues for a while, forming another planning phase. Thus, every time one task ends and/or another task begins, a new trailer routing is implemented. Note that the whole planning is performed in advance and prior to the launching of the handling task.

We then examine the distance savings and consequently the trailer fleet reduction in 10 samples of the 32 problems with 10 planning horizon spans.

Fig. 7 shows average distances traveled over the 10 computation samples in different problem settings. Note that like the distance reduction for the single span problem as shown in Table 3, there was no significant difference in the distance between stack arrangement types 1 and 2; consequently, only the results for type 1 are shown in the figure. The distance of the dynamic itinerary is shorter than that of the static one, except for the cases with the six-container capacity. The gap in the distance is more significant in the six-berth problems than the four-berth ones. The basic trend of these observations is the same as the one for the single span problem.

Fig. 7

In the fleet size computations, we assume three different types of vehicles: AGV, conventional trailer and multi-trailer. Suppose that trailers with a single container capacity are engaged at one cycle of the container movement between quay cranes and storage areas. The trailers have a much longer cycle time in returning to the quay cranes after container delivery, compared to the cycle time of the quay cranes in moving one container. Therefore, the required number of trailers has to be computed so that any unproductive suspension in quay crane movement is avoided.

The quay crane operation cycle is assumed to be 1.5 min per move, while in reality it fluctuates slightly. The speed of the given vehicles are: AGV=5km/h, Conventional trailers=15km/h and Multi-trailer=12km/h. The simulation runs as follows. According to an itinerary given from the experiments shown in Fig. 7, a trailer visits quay crane sites and container stacks with tasks of handling export and import containers: ADs, ALs, CDs and CLs. If a quay crane is not ready to treat a trailer upon its arrival, the trailer waits for the crane. Upon completion of the relevant task to the crane, it goes to the next place. In the case of multi-trailer, it does not leave a handling site (quay crane or stack location) till all relevant container moves are finished. Due to a deterministic cycle time of crane movement, one run of simulation defines a length on itinerary in time. The number of trailers required, so that as mentioned above, no delay of quay crane movement takes place, is given by the following formulation:

$$\text{The number of trailers engaged in an itinerary} = \frac{\text{a length of the itinerary in time}}{\text{a cycle time of a quay crane}}$$

Note that for simplicity, a null handling time is assumed when containers are delivered to or picked up from trailers at container stacks. This assumption is justified especially when yard-gantry cranes are well scheduled for those tasks resulting in uninterrupted trailer movement.

Whenever ships change their handling tasks, the number of trailers engaged varies because the resulting routing structures alter. The fleet size of the trailers needed for the whole planning period corresponds to the maximum number of trailers needed among the fleet sizes for the different routing structures. The costs of the vehicles by capacity, including the capital cost measured by the annual depreciation charge with 7 years of life and the operating cost for driver (not applicable for AGV), maintenance and fuel, are estimated by referring to a report from Costal Development Institute of Technology (1996) and are shown in Table 4. As only the costs for conventional trailer (with capacity of one container) and AGV are available in the literature, those for multi-trailers carrying two, three and six containers are deduced based on the single-container trailer. Note that except for AGV, the cost per vehicle covers a tractor together with trailer(s). Also, notice that except for the fuel cost, all the operating cost elements are assumed constant regardless of the amount of workload for specific time duration. In addition, as no detailed information on the fuel consumption rate both in loaded and empty runs is available, the fuel cost shown in Table 4 was applied for both runs.

Table 4

Fig. 8 portrays comparisons of the number of vehicles and associated costs between static and dynamic vehicle assignments with stack arrangement type 1. The dynamic assignment results in approximately 20% savings in fleet size and cost from the static assignment for conventional trailer, 15% savings for AGV and 10% savings for multi-trailer cases with less than six container capacity. Lower savings for multi-trailer may be caused by that the multi-trailer is already efficient in routing by the static assignment. Note that the dynamic assignment is worse for multi-trailer of six-container capacity. If we had the optimal solution to the MTP, we would have no more multi-trailers with the dynamic assignment than the static one. However, as mentioned in Section 5.2, this is not the case for the MTP since the GA is a heuristic. The overall trend of experimental results with arrangement type 2 is almost the same as type 1.

Fig. 8

In the above discussion, we determined the number of yard trailers deployed based on the relationship between trailer route length and cycle time of quay crane where the different number of trailers are assigned to each quay crane. Assuming that equal amount of trailers are allocated to each crane, we next proceed in varying the number of trailers assigned to a crane in order to examine how the trailer fleet size influences the ship's service time. The service time of a ship is computed by summing the time of handling each container relevant to the ship, which includes the cycle time of a container move by a quay crane and the waiting time of the crane for a trailer to come for both export and import tasks. If the sufficient number of trailers is provided, there is no waiting time to be included as no unproductive interruption of the crane occurs. If a trailer does not arrive in time at a quay crane site, the waiting time of the crane is cumulated in the service time of the relevant ship. In reality, in addition to the time spent for handling container, the service time includes the time for opening and closing hatch covers, etc.; however, such details were ignored in the experiments.

Fig. 9 illustrates ship service times in a six-berth terminal with different trailer fleet sizes and different trailer capacities, assuming all quay cranes engage the same number of trailers. The ship service time obviously decreases with increasing the number of trailers.

More interestingly due to widespread ship locations at the multi-user terminal, there is a large fluctuation in the service time with the identical, fewer number of trailer assigned to each quay crane. Also it is interesting that the service time is smaller with the dynamic assignment than the static assignment.

Fig. 9

5.4. Solution quality of the GA

This paper approximates a solution for the MTP. In the GA literature, the GA based algorithm produces fairly good solutions, although most papers do not offer intensive discussions about the solution quality. As the GA is applied to problems of huge size, difficult to solve in terms of realistically acceptable computation time, very few problem samples or very small sizes of those could be analyzed comparatively between GA solutions and exact solutions. This is also the case here. As discussed in the Section 3, the MTP with trailer capacity of one container is reduced to the STP that is formulated as an assignment problem and is solved exactly and efficiently by the Hungarian method. Therefore, approximate solutions by the GA heuristic for the MTP can be compared with the exact solutions even for the trailer capacity of unity. We made the comparisons between solutions by the formulations [ST2] and [MT] for the 10 samples of the eight problem cases as defined in Table 2. Fig. 10 reveals percent gaps in solution quality, as defined in Eq. (19), only for four out of the eight problem cases, i.e., cases 2, 4, 6 and 8 with six berths.

$$(SM - SS)/SM \times 100 \quad (19)$$

where SM is the distance obtained by the MTP whilst SS is the one by the STP.

Fig. 10

Although there is a much less fluctuation over the solution gaps of the ten different problem samples with four berths, the trend is almost the same as the gaps of the samples with six berths.

The graphs demonstrate the gaps for the 10 computation samples and the average value of those samples (abbreviated as AVG in the figure). Besides the number of berths, the number of cranes engaged also defines the problem size. In this respect, the GA represents its inferiority in solution quality; however, the difference between the two solution methods is quite small. As far as the stack arrangement is concerned, type 2 shows slightly superiority in solution quality. Type 1 has containers spread out in the yard, thus resulting in increased difficulty in route configuration. To summarize, the problem size and potential difficulty in forming route configuration affects the solution quality of the GA procedure.

As most gaps (including four-berth cases) are less than 10%, the GA works fairly well and the solution quality is acceptable even though this insight is true only for the single capacity trailer.

The dynamic trailer assignment (or routing) developed here is superior to static one, which is popular at most terminals, since the former reduces capital and operating terminal costs. As shown in the above experiments, the cost reduction results from a shorter total travel distance of trailer at a maritime container terminal by the dynamic one than the static one.

6. Conclusions

In this study, we addressed the dynamic assignment rules of yard trailers to quay cranes and the associated optimization of trailer routing. At a dedicated container terminal, a set of trailers is in general assigned to a specific quay crane until the work is finished. We examined another type of assignment, which we named "dynamic assignment (or itinerary)", aiming to increase the productivity of the terminal. The problem can be defined by two formulations: one for trailer capacity of one container, the other for trailer capacity of more containers. Although the former is a particular case of the latter, it can be treated separately due to the easiness in its solution methodology.

Throughout a broad range of computational experiments, it was demonstrated that the dynamic assignment is superior to the static assignment with respect to the trailer distance traveled and consequently to the required fleet size. Trailer fleet cost savings in the order of 15% are obtained using the dynamic assignment compared with the static assignment.

The GA procedure that is employed for solving the problem for trailer capacity of more than one container is a heuristic and does not necessarily provide an optimal solution.

On the other hand, the algorithm for problems with one container capacity can identify an optimal solution efficiently because it is formulated as an assignment problem. Therefore, for the single capacity problems, we can analyze the solution quality of the GA procedure. According to computational comparisons between the GA and assignment problem, the former yields solutions whose objective function values are at most 20 % higher than those of the assignment problem. On average, the former solutions are less than 10% worse and this figure seems acceptable.

We conclude that the dynamic trailer assignment developed in this paper is superior to the static one, which is popular at most terminals, since the former reduces capital and operating terminal costs. As shown from the examination of the computational experiments' results, the cost reduction turns out to be possible through the reduced trailer fleet size deployed, which results from the shorter total travel distance (more precisely shorter empty travel distance) of trailers employed through a dynamic assignment rather than a static one.

This paper's contribution to the literature is the development of new, efficient routing principle of trailer at a maritime container terminal and the implementation of the heuristic algorithm to identify a near optimal solution to the routing problem, both of which save yard operation time and costs.

As this trailer routing has practical applications, port operators may look into ways of implementing it. The dynamic assignment principle is useful to the container terminal management for both tactical and operational decisions. For example, terminal operators can simulate the trailer routing or movement while they are engaged in ship handling, in order to determine the trailer fleet size to be deployed when planning new terminals. In the operational stage the stevedoring companies can simulate the trailer movement in order to make up a daily or weekly trailer work schedule given a prospective cargo handling profile.

The only drawback to the use of the dynamic assignment is the complexity of the trailer routing, which may increase the possibility of human error. Trailer drivers may find difficult to follow the complicated itineraries assigned to them, resulting in mistakes in driving. However, such types of errors could be minimized through the use of proper communication and tracking systems.

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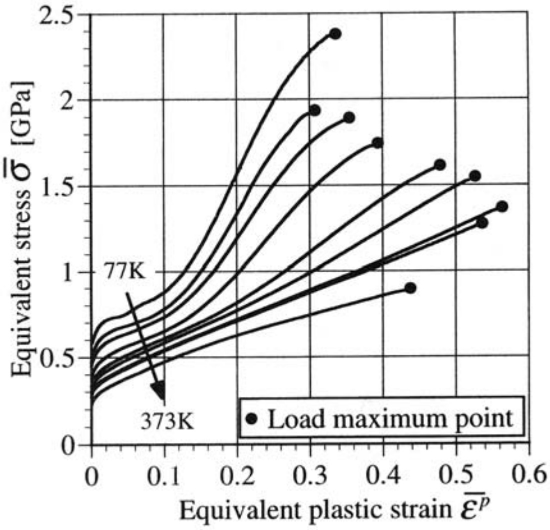

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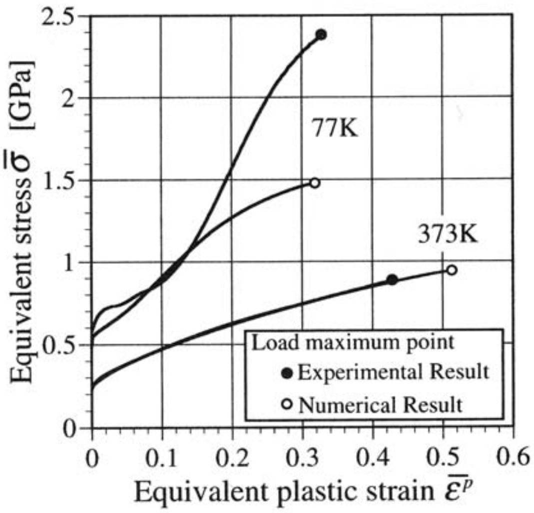

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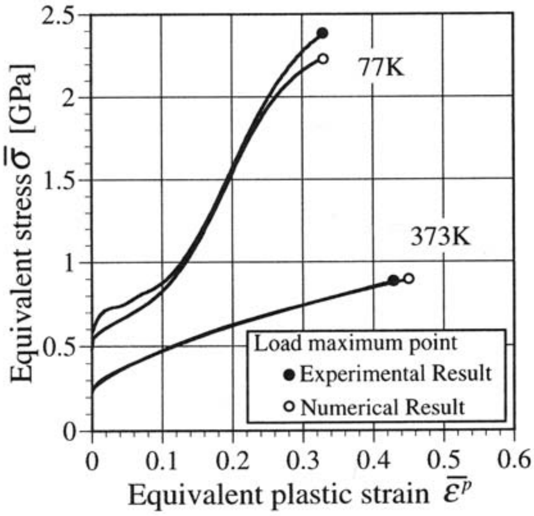

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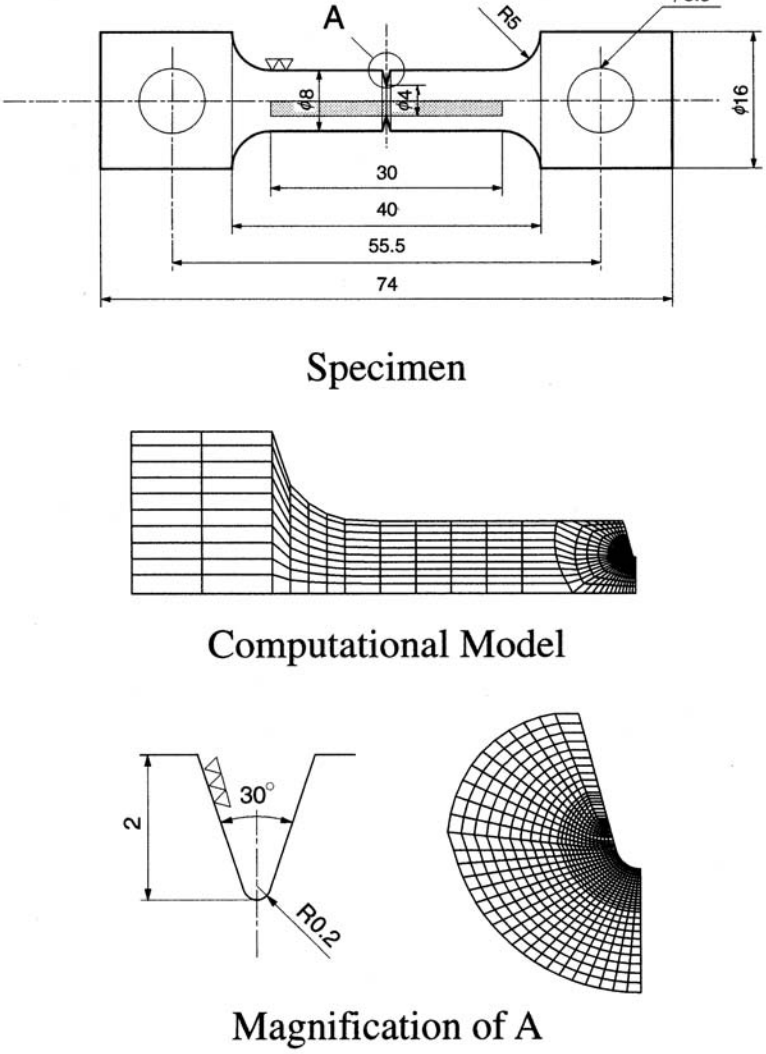

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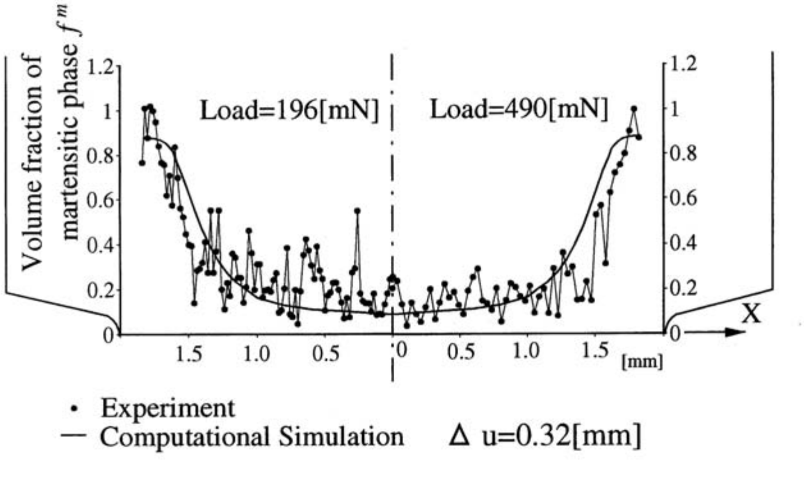

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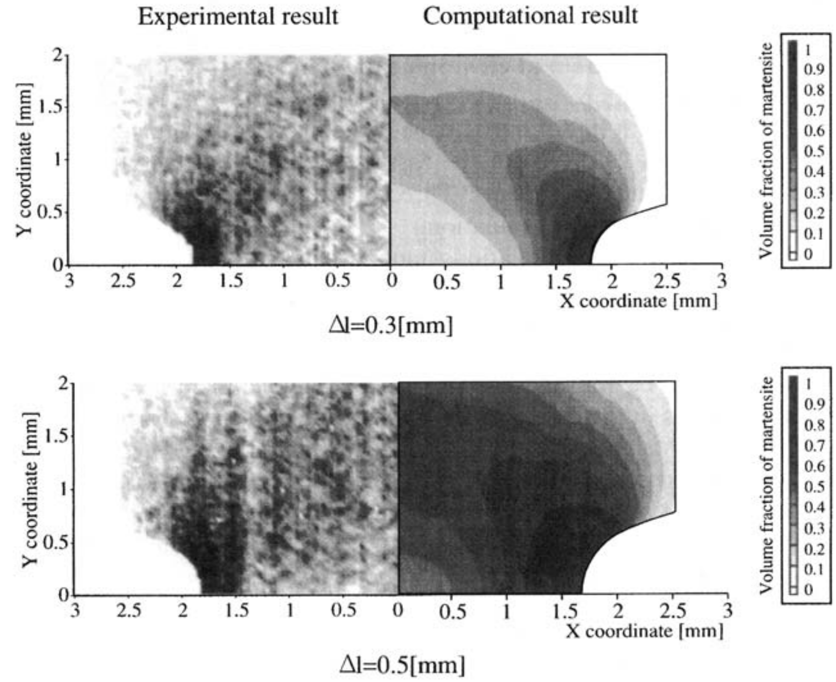

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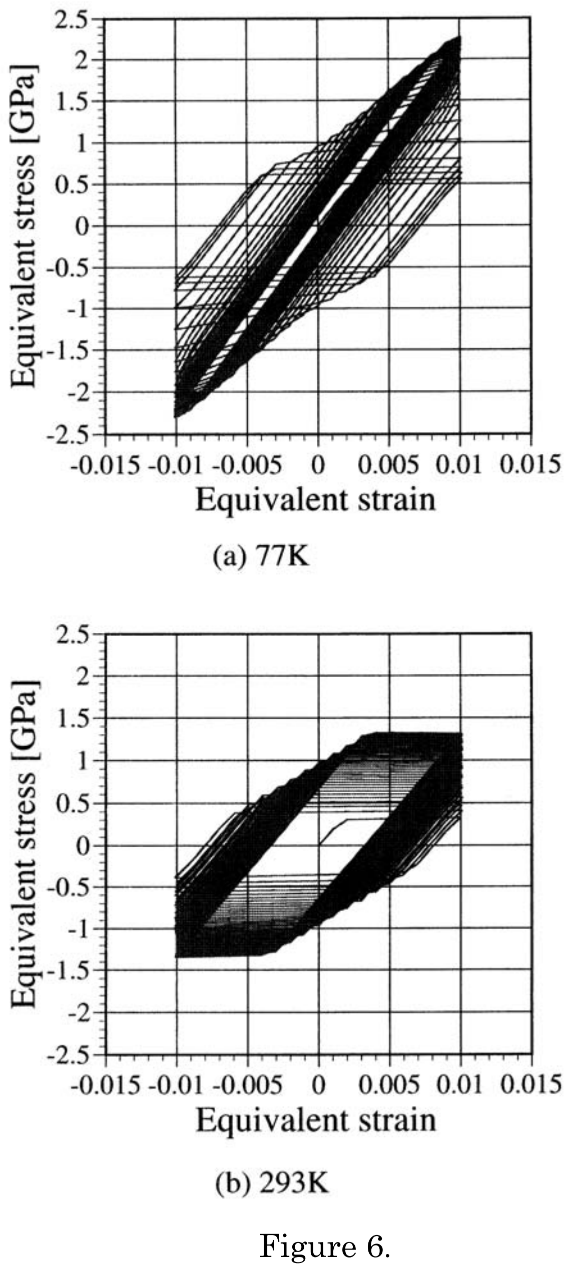

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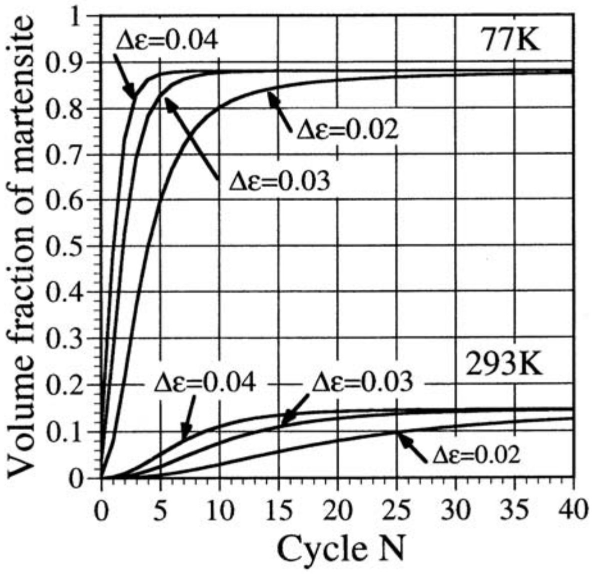

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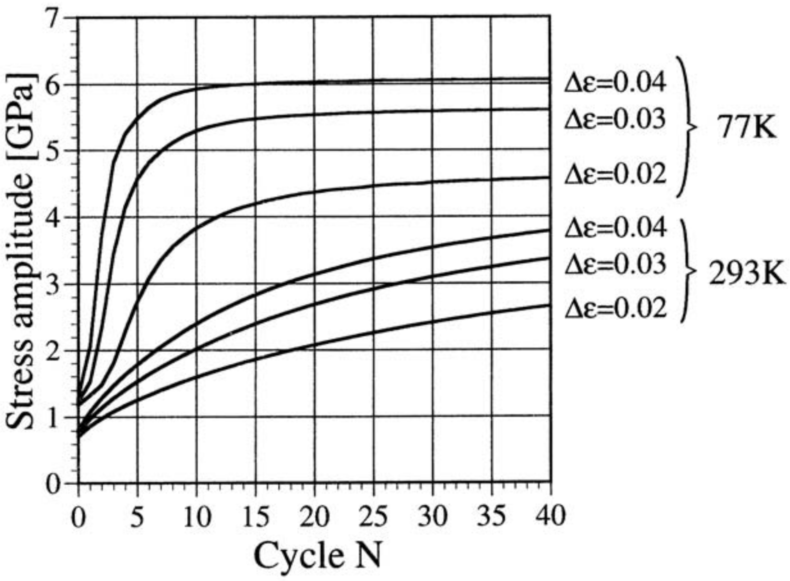

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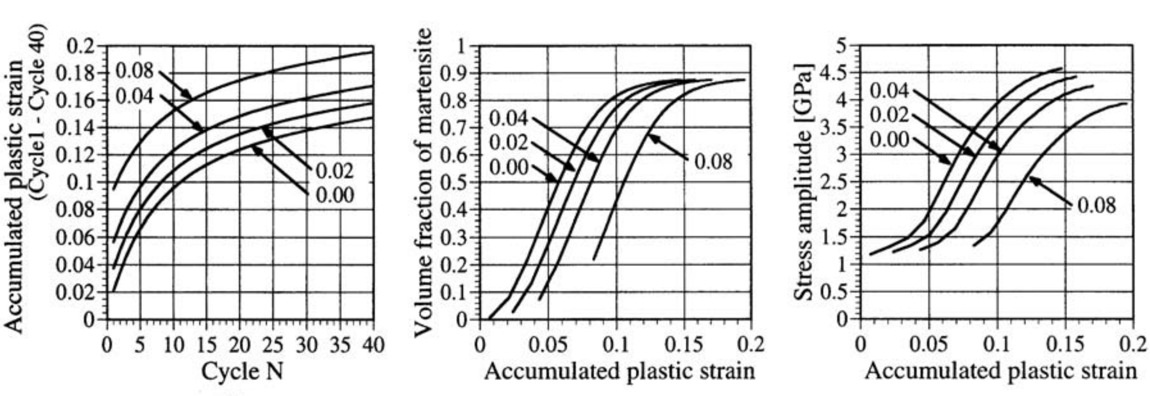

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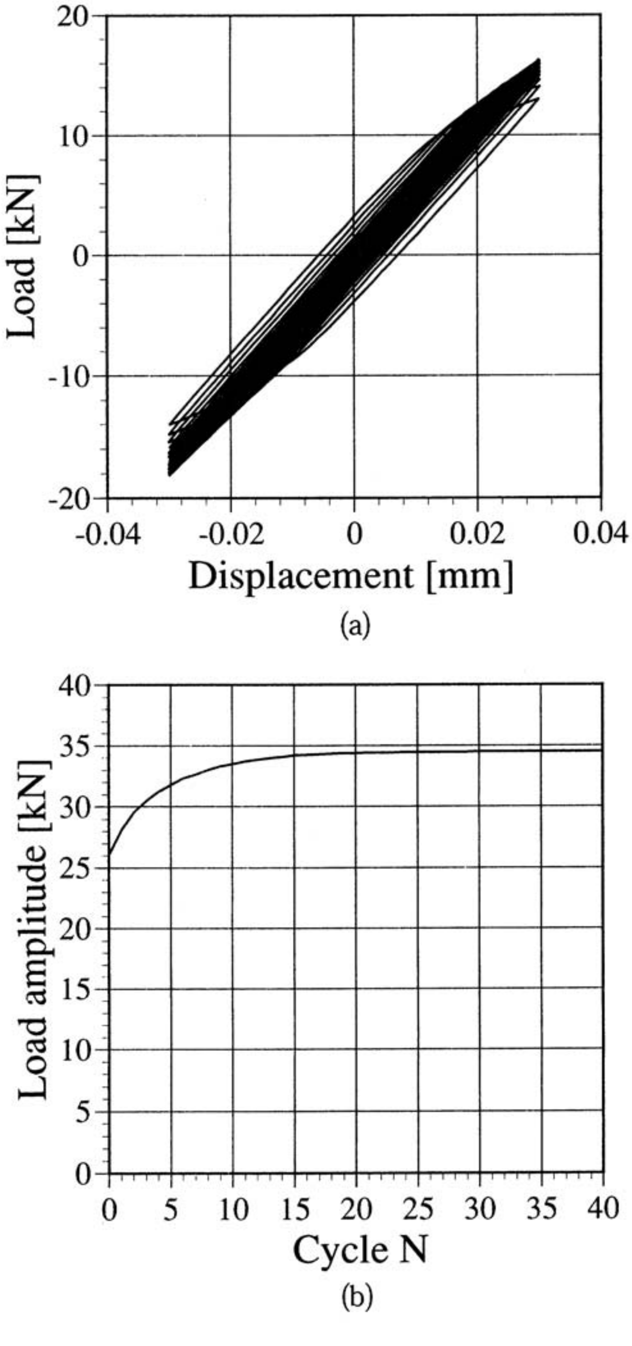

20
10
0
-10
-20
Load [kN]
-0.04
-0.02
0
0.02
0.04
Displacement [mm]
(a)
40
35
30
25
20
15
10
5
0
Load amplitude [kN]
0
5
10
15
20
25
30
35
40
Cycle N
(b)

Figure 9.

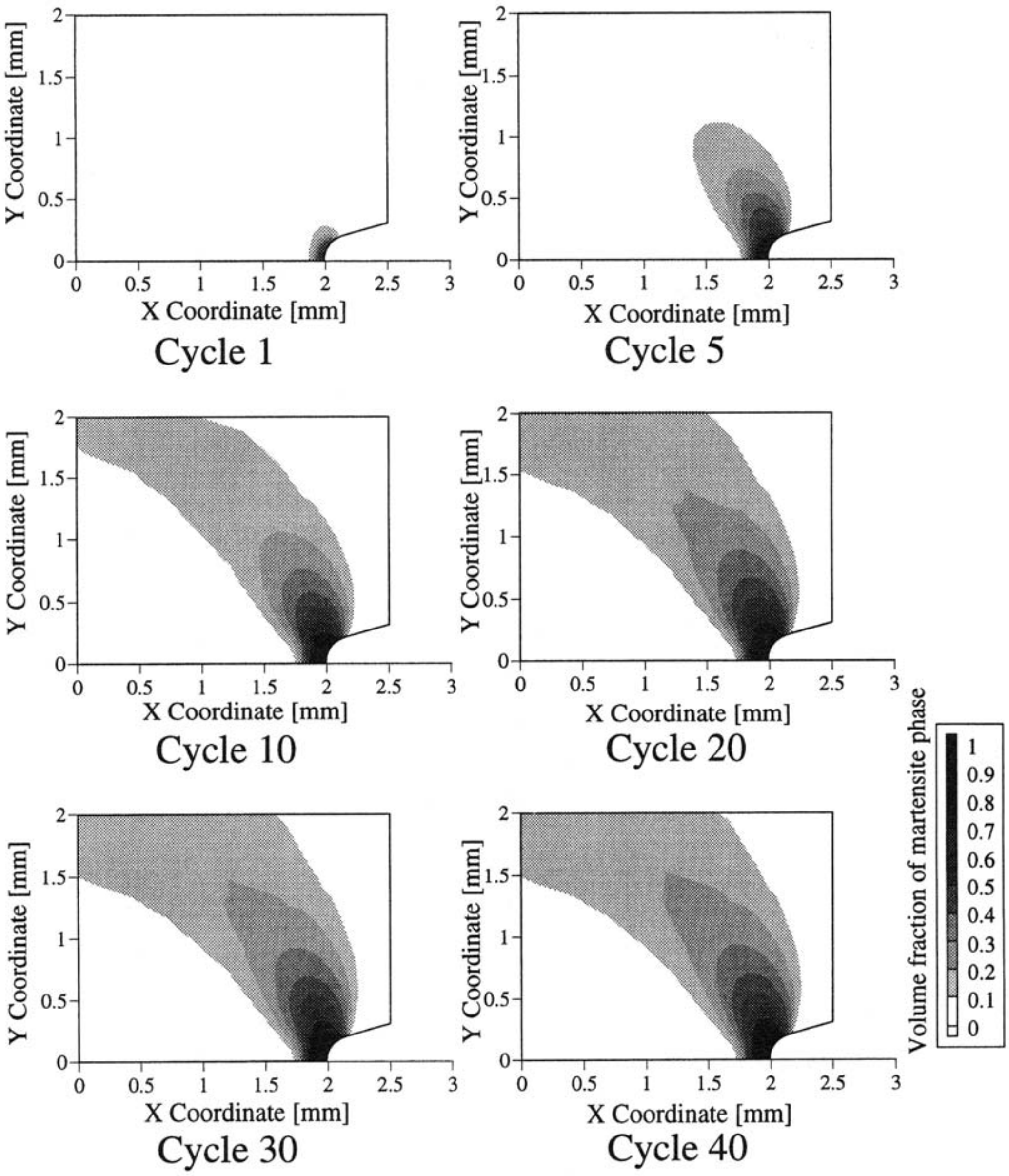
Y Coordinate [mm]
X Coordinate [mm]
Cycle 1
Cycle 5
Cycle 10
Cycle 20
Cycle 30
Cycle 40
Volume fraction of martensite phase
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Figure 10.

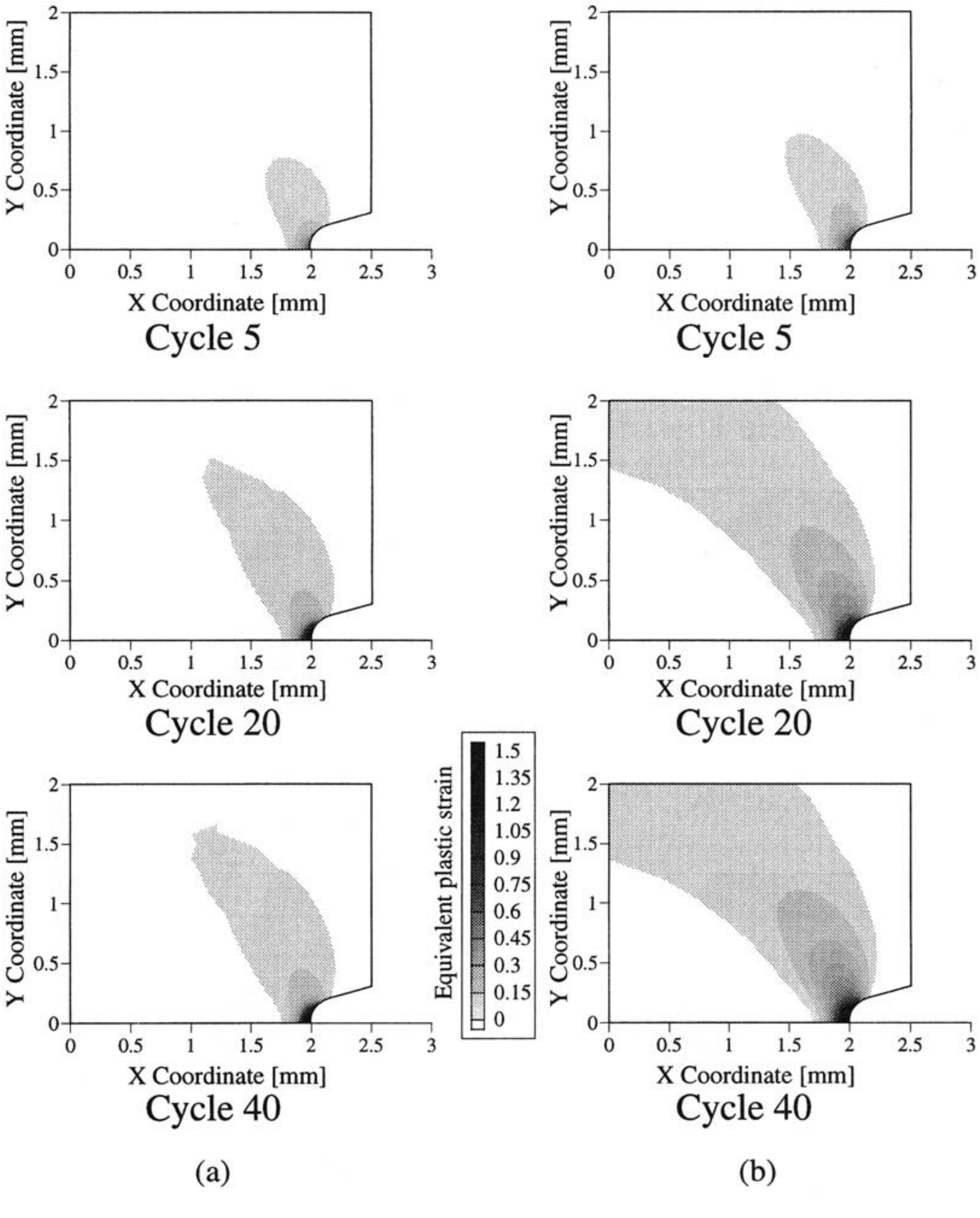
Y Coordinate [mm]
X Coordinate [mm]
Cycle 5
Cycle 20
Cycle 40
Equivalent plastic strain
1.5
1.35
1.2
1.05
0.9
0.75
0.6
0.45
0.3
0.15
0
(a)
(b)

Figure 11.

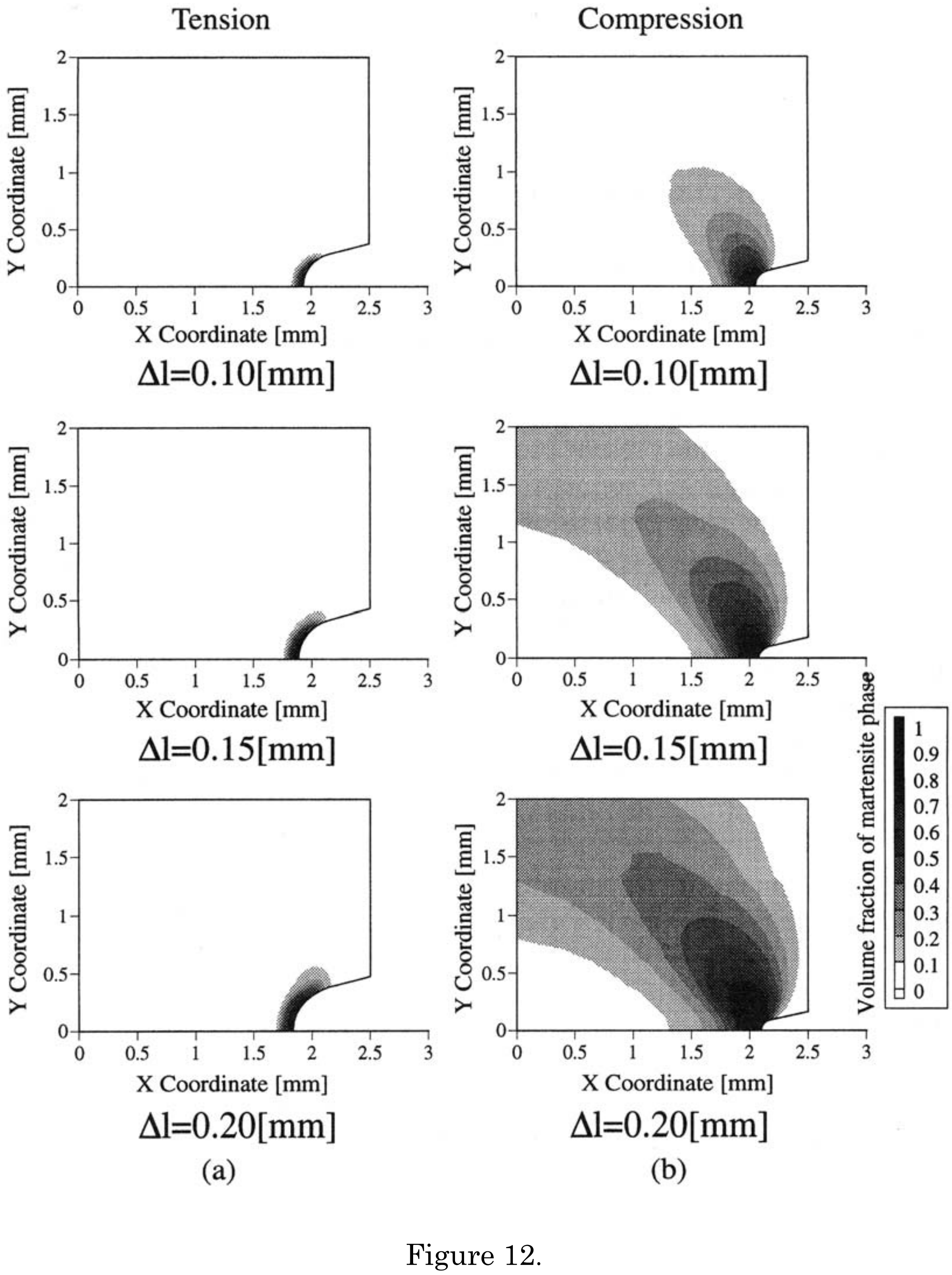
Tension
Compression
Y Coordinate [mm]
X Coordinate [mm]
Δl=0.10[mm]
Δl=0.15[mm]
Δl=0.20[mm]
Volume fraction of martensite phase
(a)
(b)

Figure 12.